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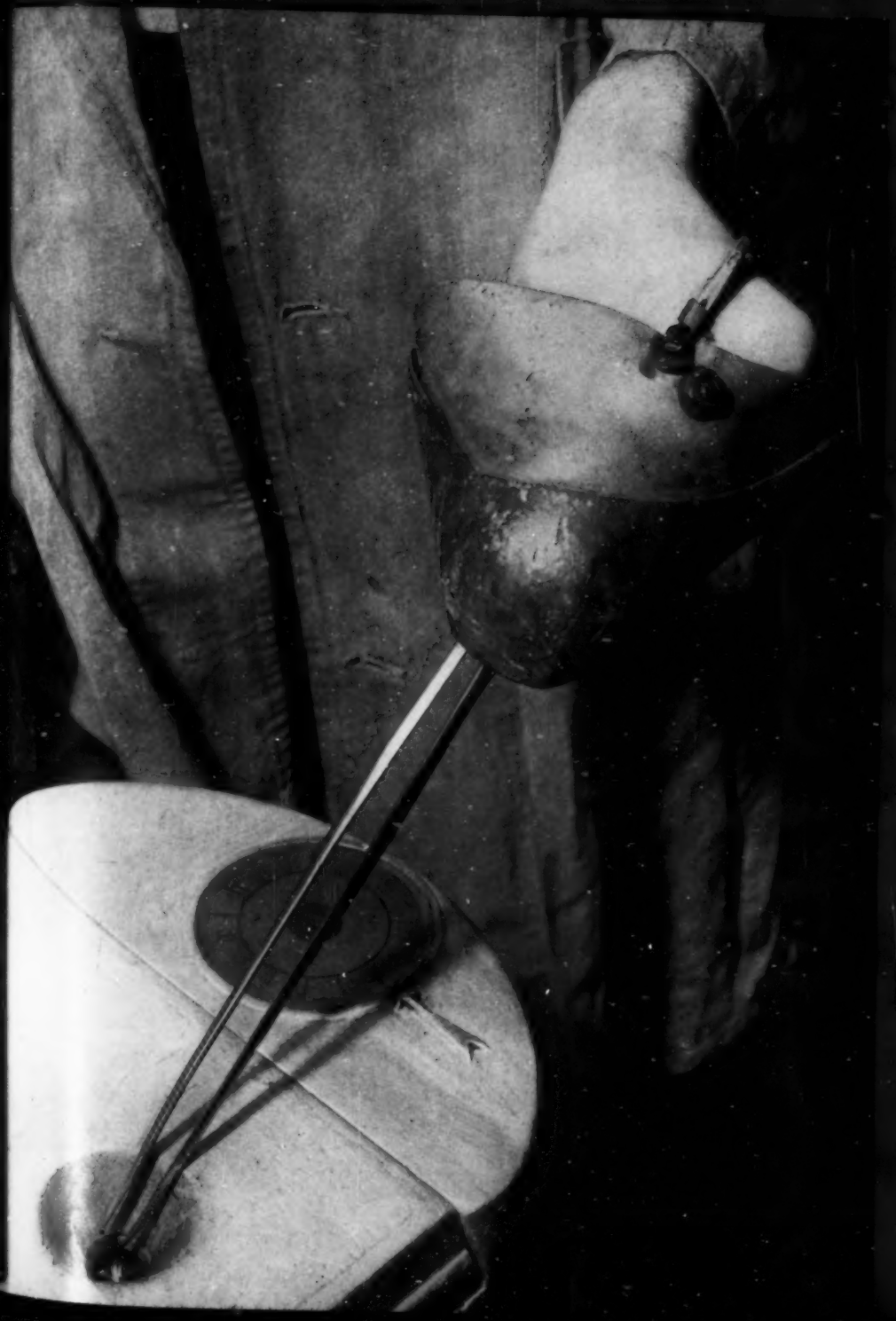

SEPTEMBER
1939

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JOURNAL OF APPLIED

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SEPTEMBER, 1939 Vol. 10, No. 9

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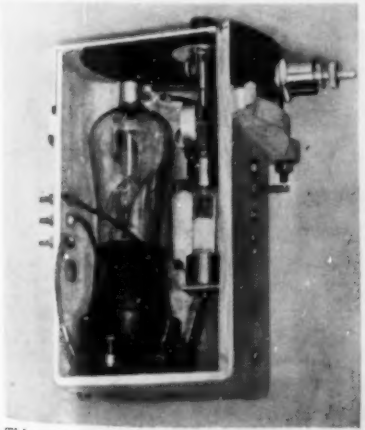

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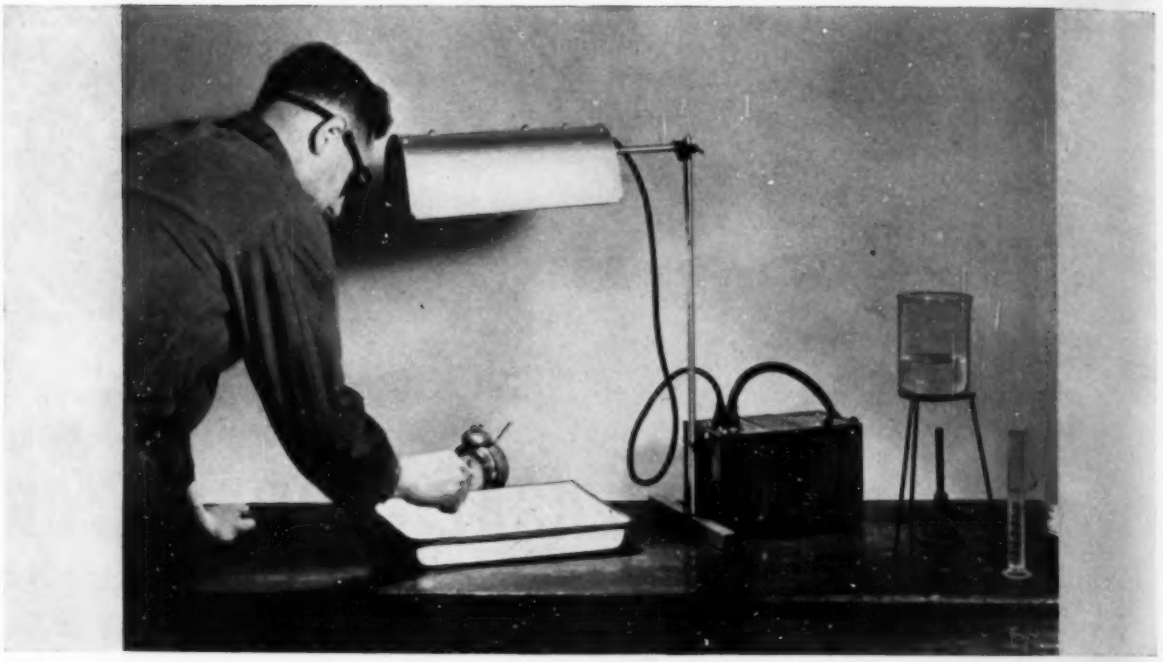

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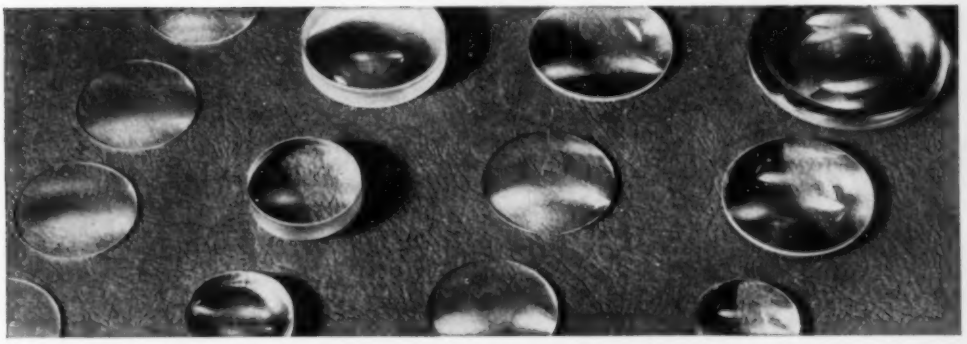

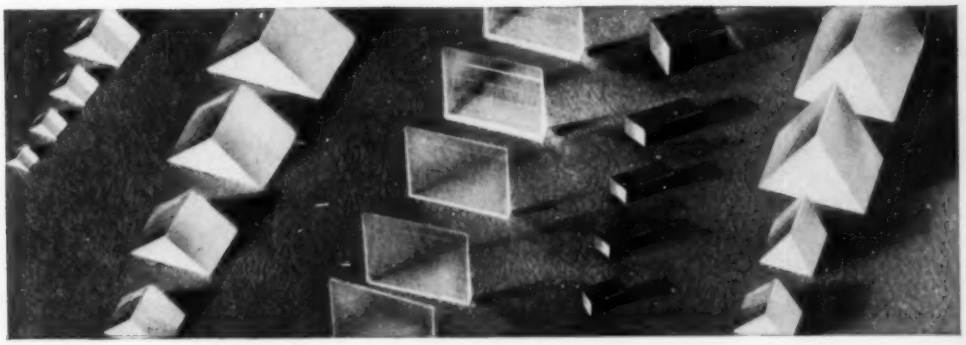

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Research—A National Resource

THE volume entitled *Research—A National Resource*[1] published under the auspices of the National Resources Committee does not seem to be very well known. It is the first of a series of reports being prepared by this committee and has as its primary purpose a study of the various research agencies of the Government and a consideration of possible correlation of the work within these agencies and of their work with that of university and industrial research organizations. In keeping with this purpose the first section of the report deals with the relation of the Federal Government to research. The second section gives a group of eight supporting studies. Particularly interesting are the ones on the Research of the Federal Government in the Natural Sciences and Technology and Research in American Universities and Colleges.

The research activities of the Federal Government are naturally of a very broad scope. One used to physical research will raise his eyebrows at some of the work classified as research, but leaving aside doubtful subjects, there is still a great variety of research projects. The principal fields of study in which research is done are: (1) public health, (2) agriculture, (3) national defense, (4) population, (5) weather, and (6) social science, which includes great questions of mental health, crime, labor relations, finance, international relations, etc.

[1] *Research—A National Resource, I*, Relation of the Federal Government to Research (United States Printing Office, Washington, D. C., 1938), 255 pp., price 50 cents.

Rather conspicuous in the Government program is the lack of fundamental research in the natural sciences. It may be that such research is carried on sufficiently well in university and certain industrial laboratories. One wonders, however, whether pure science research is not a function of the Federal Government. A government such as ours is essentially a group of men elected to initiate and carry out projects which benefit the nation as a whole. Great praise has been given to those who formulated the Constitution because of their foresight and long-time point of view. If one assumes that a federal government should do those things which will benefit people generally not only immediately, but also in the years to come, surely the support of fundamental research is one of its functions. Thus, in a discussion of "Research—A National Resource," does it not seem strange to pass over almost entirely the responsibility of the Federal Government to undertake and to support fundamental research? Such research in the past has paid larger dividends than almost any other human activity.

In spite of the lack of emphasis on fundamental research in this report, those who are interested in seeing more research carried on will welcome it with open arms. Recommendations are made in it for better correlation of the research activities of the universities and those of the Government. Undoubtedly, much good will come from this study and the National Resources Committee is to be congratulated on doing a fine job.

The Economic Features of X-Ray Protection*

BY LAURISTON S. TAYLOR

National Bureau of Standards, Washington, D. C.

This paper is the first of a series of three papers on the precautions which must be taken when working with x-rays, radium, or neutrons. The present paper is concerned with x-ray protection. The following paper in this issue describes the precautions to be used in the handling of radium or other radioactive preparations. A third paper dealing with the protection required where fast neutrons are being produced will be published in the near future. —Editor.

Introduction

PROTECTION against undesired exposure to x-rays or the gamma-rays from radium can be had, but for economy and convenience it is desirable to analyze closely, with certain fundamental principles in view, each particular problem. Basic rules for x-ray and radium protection have been promulgated by the International Commission on X-Ray and Radium Protection and published in numerous journals. More detailed rules, prepared in this country, are available in NBS Handbook 20 (*X-ray Protection*)** and NBS Handbook 23 (*Radium Protection*).**,[1] Reference to these is recommended before planning a new x-ray installation.

The handbook on x-ray protection gives the rules for maximum protection; if followed strictly, any errors will be on the safe side, though not necessarily the most economical one. We give, in these discussions, certain qualifications which may permit a more economical disposition of protective barriers and devices. At the same time a number of miscellaneous points requiring special emphasis are considered.

The tolerance dose recommended by the International Protection Commission is taken as a 7-hour daily exposure at a dosage rate not exceeding 10^{-5} roentgen per second. This is roughly 10^4 times the dosage rate of cosmic radiation. It is argued by the geneticists, that this is 10 times the safe dosage; or, in other words, the tolerance dosage rate should not exceed 10^{-4} r/sec. Their figure is based on the elimination of any second generation genetic effects, whereas the accepted figure of 10^{-5} r/sec. is based on the effect upon the recipient of the radiation only. Although genetic effects were not a consideration during the preparation of the international safety recommendations, it is possible that such a wide margin of safety has been provided that they have hitherto successfully protected against genetic mutations.

Lead Protective Barriers

Since lead has the highest atomic number of any material readily available and easily worked, it is generally used for protective barriers and the protective value of other materials is referred to lead as a base.

Figure 1 gives a set of lead absorption curves in the x-ray excitation range of 200–400 kv produced with a Villard rectifier[2] and having an initial filtration of 1 mm Cu+1 mm Al (hence fairly hard radiation). Starting with a relative dosage rate of 10^4, the absorption measurements for the several voltages are carried out until the dosage rate has been reduced to unity.

Table I gives the thickness of lead necessary for adequate protection as prescribed by the International Commission on X-Ray and Radium Protection.[3] It is obvious that the figures can apply only to an incident beam of one given dosage rate at a definite distance from a given x-ray tube.

The protective lead thicknesses given in

TABLE I. *Mass in pounds per sq. ft. of lead barrier for adequate protection.**

Potential	Recommended minimum lead thickness	Weight of barrier	Potential	Recommended minimum lead thickness	Weight of barrier
1	2	3	1	2	3
kv	mm	lb./ft.²	kv	mm	lb./ft.²
75	1.0	2.4	225	5.0	14
100	1.5	3.5	300	9.0	21
150	2.5	5.9	400	15.0	35
200	4.0	9.5	500	22.0	52
			600	34.0	80

* Recommendations of International Commission on X-Ray and Radium Protection (1937).

* A more detailed discussion will be published at an early date in *Radiology*.

** These can be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C., at a cost of 10¢ each, (stamps not accepted), mailed free.

Table I are self-consistent in that they all give the thickness of lead required to reduce the beam produced at any given voltage by approximately the same amount. *It is further found that the internationally accepted protective lead thicknesses all apply to an initial dosage rate of 3 roentgens per minute at 150 cm from the target.* In other words an incident dosage rate of 3 r/min., at a given voltage, will be reduced to 10^{-5} r/sec. in passing through the corresponding lead barrier.

In the examples given below we will use an average incident value of 6 r/min. (or 0.1 r/sec.) at a distance of 100 cm from the target which will introduce only a slight difference from the figure derived from the international recommendations.

To simplify the calculation of lead thicknesses for different incident dosage rates (as affected by target distance and tube output) Herrmann and Jaeger[2] have replotted their data, Fig. 2, to show directly the amount of lead which must be inserted in a given beam to reduce the transmitted dosage rate to 10^{-5} r/sec. For example, suppose we take the case of an incident beam at 204 kv and a dosage rate of 0.1 r/sec. Referring to curve 1 it is seen that 4.2 mm of lead is required to reduce the dosage rate to the tolerance value of 10^{-5} r/sec. This is seen to be in agreement with the discussion above for the average conditions at 100 cm. If, on the other hand, it is desired to reach the safe tolerance dose after passing through a lead barrier located at a distance of 4 meters from the tube, the incident dosage rate on the lead barrier is then reduced by inverse square law to $\frac{1}{16}\times 0.1$ r/sec. $=0.0063$ r/sec. $=6.3\times10^{-3}$ r/sec. Again on curve 1, the point 6.3×10^{-3} r/sec. corresponds to a required lead thickness of 2.7 mm to reduce the transmitted radiation to 10^{-5} r/sec. If, instead of the average output of 0.1 r/sec., the output is, say 0.033 r/sec., then the dosage rate at 4 meters would be reduced to $0.033/0.1\times6.3\times10^{-3}$ r/sec. $=2.1\times10^{-3}$ r/sec.; for which the curve would show a required thickness of 2.2 mm of lead to reduce the radiation to the tolerance value.

At the higher voltages real economies may be effected by careful consideration of the distance and output factors. Let us take the same conditions at 408 kv, and refer to curve 5, Fig. 2. For an incident dosage rate of 0.1 r/sec. at 1 meter, a lead thickness of about 17 mm is necessary to

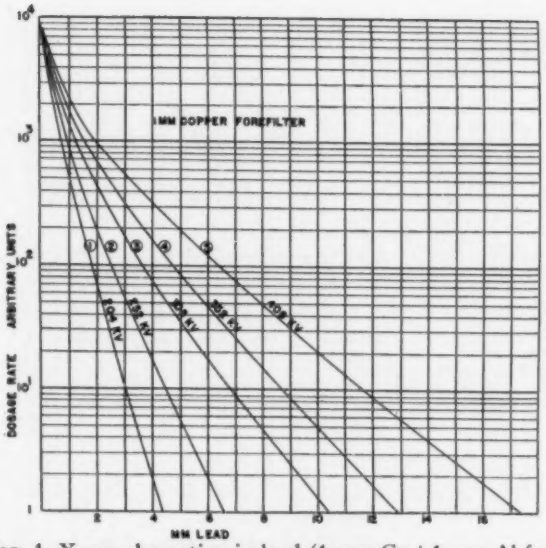

FIG. 1. X-ray absorption in lead (1 mm Cu+1 mm Al for filter). (Herrmann and Jaeger.)

reduce the beam to the tolerance value. At 4 meters the incident dosage rate is again 6.3×10^{-3} r/sec. and the required protective thickness is seen to be only 10.5 mm or a reduction of 35 percent. If again the tube output at 100 cm is reduced from 0.1 to 0.033 r/sec. the incident dosage rate at 4 meters is as before 2.1×10^{-3} r/sec. and the corresponding protective thickness is 8 mm of lead or a reduction of 53 percent. It is thus clear that in the higher voltage ranges very considerable economies may be effected by considering all of the conditions involved in a particular installation.

Use of Hermann and Jaeger's curve in the manner just described applies only to conditions where the initial reduction in x-ray dosage rate is due to scattering from the main beam, tube distance, changed tube output, etc., and is unaccompanied by a hardening of the radiation. Where a decrease in dosage rate is caused by filtering, and hence is accompanied by hardening, the necessary lead thicknesses must be determined beginning at the other end of the curve and using the inverted scale of dosage rates indicated at the right of Fig. 2.

To give an example, suppose we wish to compute the protection necessary in a wall 2 meters away from a lead-covered 400-kv tube inclosure, where this lead is sufficient to reduce the dosage rate to 10^{-3} r/sec. at a distance of 1 meter from the enclosure. In this case the radi-

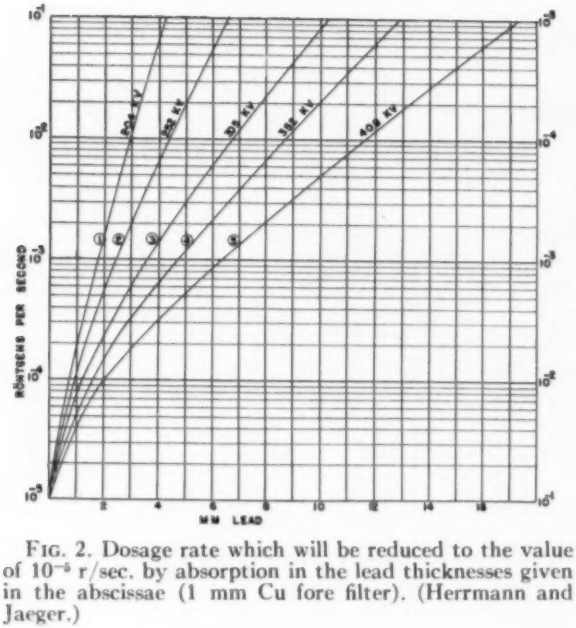

FIG. 2. Dosage rate which will be reduced to the value of 10^{-5} r/sec. by absorption in the lead thicknesses given in the abscissae (1 mm Cu fore filter). (Herrmann and Jaeger.)

ation is obviously harder than that in the unfiltered beam. The inverse square law will give at 2 meters an intensity of $(1^2/2^2)\times10^{-3}$ r/sec. $=2.5\times10^{-4}$ r/sec. Using the dosage rates indicated at the right of Fig. 2 it is seen that on the 400-kv curve to reduce the dosage rate from 2.5×10^{-4} to 10^{-5} will require $17.7-10.4$ mm or 7.3 mm of lead. Had the original radiation been unfiltered, the lead required for protection would have been figured from the left-hand set of dosage rates and would be 3.5 mm.

In Table II are given the weights in pounds per square foot of different lead thicknesses; the cost per square foot at an average price of 10¢ per pound; and also an estimate of the installation costs. The figures for installation are, of course, very rough and include the supporting partition of hollow tile or brick with the necessary furring to support the lead. The cost of finishing the plaster, etc., is about the same for all thicknesses. For protection at the lower voltages the cost of the supporting partition is comparable with that of the lead, while for protection at the higher voltages the cost of the lead is predominant.*

* The installation costs above 300 kv are difficult to estimate and are probably low. It is quite likely that for weights above 20 lb./ft.^{2} a special steel frame or concrete wall construction would be required for support of the lead necessary at the higher voltages. For a ceiling or floor the lead may be simply laid on the floor and then covered with some suitable decking.

Other Protective Materials

Because of the high cost of lead protection, use of other materials, such as concrete or brick, has been resorted to with some success. Also, concretes "loaded" with barium sand, iron filings or iron ore have been used. However, it is important to emphasize that a lead barrier will provide the lightest installation per given degree of protection (within the voltage range of 50–600 kv). Any of these substitutes will be from 2 to 20 times heavier; but this higher load may be offset by the concrete or brick having definite structural value and thus provide economics in general building construction.

Singer[4] has shown that at a given excitation between 200 and 400 kv the protective value of concrete is proportional to its density and Kaye[5] has shown proportionality for other materials.

TABLE II. *Costs of lead walls.*

KV	LB./FT.^{2}	$/FT.^{2}	INSTALLED UNFIN.*	INSTALLED FIN.†
100	3.5	$0.35	$0.85	$1.20
200	9.5	.95	1.45	1.80
300	21.	2.10	2.70	3.05
400	35.	3.50	4.10	4.50
500	52.	5.20	6.00	6.50
600	80.	8.00	9.00	9.50

* Lead fastened to furring on terra-cotta wall.
† Lead covered with lath and plaster.

We thus have the choice of making a thin wall of dense "loaded" material or a thicker wall of standard unloaded material. The relative costs depend largely upon the geographical location with respect to iron mines or barytes pits.

Figures 3 and 4 give, for poured concrete and concrete blocks, the lead equivalents at different voltages and thicknesses of material. The curves in dashed lines give, on the ordinates, the lead requirements of the International Commission.

The important feature about concrete protective barriers is that their protective efficiency, with respect to lead, increases with both voltage and thickness in the range above 200 kv. Since the thickness is the controllable factor it is desirable to use only the full thickness necessary for a given lead equivalence. This "optimum" thickness is found to vary only slightly with voltage above 200 kv.

Table III gives the lead equivalents of concrete for the conditions imposed by the international

protection recommendations. Column 6 shows the marked increase in the efficiency of concrete protection with increase in voltage; while column 7 shows the decreasing weight ratio of concrete to lead. In installation, the weight ratios may be smaller than shown in column 7 since the weight of wall necessary to support the lead must be taken into consideration. It is thus strikingly evident that the desirability of employing concrete as an x-ray protective material increases with voltage.

In a finished building, because of the difficulty of installing and filling the forms, it may not be easy or economical to install solid concrete walls, but in a new building concrete walls are easily made and form a structural member of the building. Costs of concrete walls and floors are given in Table IV.

Table V, column 4, shows the lead equivalent for concrete blocks for the conditions imposed by the international protection recommendations. For comparison, the lead equivalents of several other materials are also given in the same table.

The best protection in the average x-ray room may be accomplished through application of the inverse square law, for the tube is seldom closer than 3 or 4 meters to the wall which separates it from the operator. Particularly in a new building, it may be easier to place the operator and partition relatively far from the tube than to build a smaller but heavier partition near the tube. In cases where the area of the partition will not be affected by its distance from the tube, the economy of moving it away is obvious. On the other hand, where concrete replaces lead, the savings resulting from shifting the partition away from the tube is slight. Taking the 400-kv case, it is seen that 15 mm of lead or 26 cm of concrete are needed for protection at 2 meters, while 10 mm or lead or 18 cm of concrete are needed at a distance of 5 meters (see Fig. 3). The saving in cost and weight by shifting the partition is about 30 percent for lead; while for concrete, although the weight is also decreased by about 30 percent, the cost is not reduced by more than 5 to 10 percent.

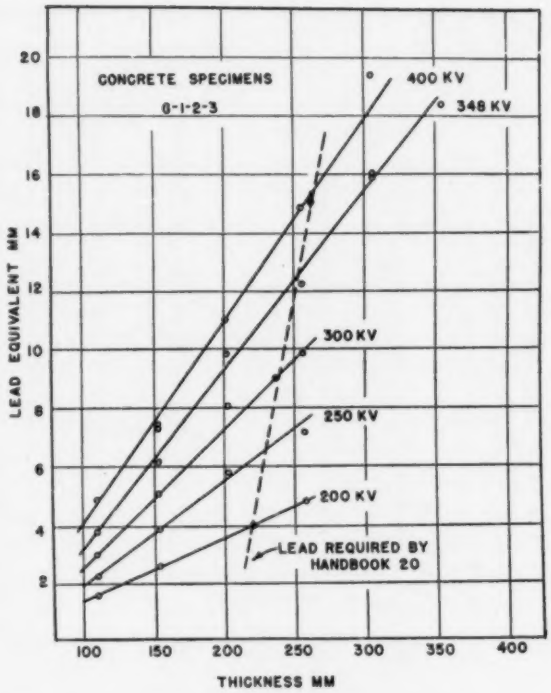

FIG. 3. Lead equivalent of poured concrete. (Singer, Taylor and Charlton.)

TABLE III. *Lead equivalents of concrete.*

1	2	3	4	5	6	7
			MASS/UNIT AREA		THICKNESS CONCRETE ÷ THICKNESS LEAD	MASS OF CONCRETE ÷ MASS OF LEAD
POTENTIAL	RECOMMENDED LEAD	CONCRETE EQUIVALENT	LEAD	CONCRETE		
kv	mm	mm	g/cm²	g/cm²		
100	1.5	120[a]	1.7	28	80.0	16.5
200	4.	220[b]	4.5	53	55.0	11.8
300	9.	240[b]	10.2	57	26.7	5.6
400	15.	260[b]	17.0	60	17.3	3.5
600	34.	300[d]	38.4	65	8.1	1.7
1000	86[f]	—	97.5	—	—	—
gamma	100[e]	540[c]	113.4	130	5.5	1.2
gamma	50	270[c]	—	—	—	—

[a] From Kaye, $\rho = 2.1$.
[b] From Singer, Taylor and Charlton,[4] $\rho = 2.35$.
[c] Calculated from Kaye, Binks and Bell,[5] $\rho = 2.35$.
[d] Extrapolated value from Singer, Taylor and Charlton.[4]
[e] From Kaye, Binks and Bell,[5] 100 mm applies to 3 grams of radium at a distance of 100 cm. 50 mm applies to 0.25 gram of radium at a distance of 100 cm.
[f] From Dresser and Cosmon[6] recalculated to accord with International Recommendation.

Protective barriers can be applied directly to the tube itself, in which case the target-lead distance may be only 10 or 15 cm. Although for a given degree of protection this requires a slightly greater thickness of lead, the amount is far smaller than that necessary for a whole partition or room. Added lead thickness applied directly to the tube lessens that required by the walls,

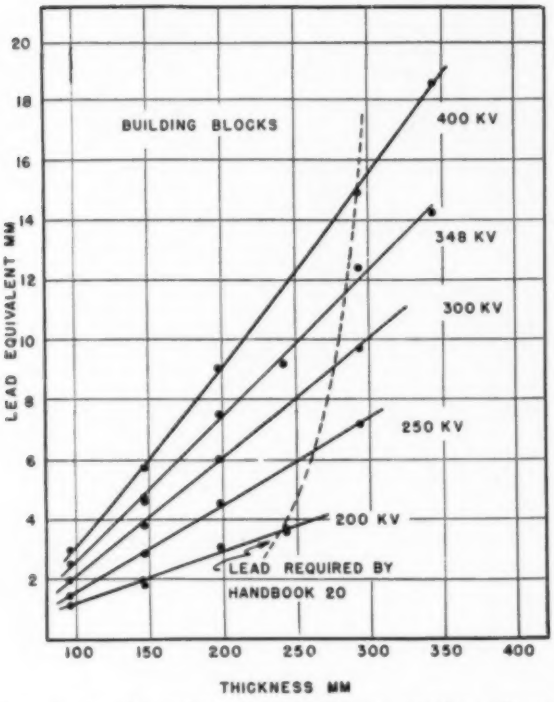

FIG. 4. Lead equivalent of concrete blocks. (Singer, Taylor and Charlton.)

up to the point where the stray radiation from the tube equals the scattered radiation from objects in the direct beam. This reduction in thickness, of course, does not apply to portions of the room reached by the main beam.

Protection Against Scattered Radiation

Thus far the discussion has been limited primarily to protection against direct radiation. But scattered radiation is always present and must be reduced to at least the same end value as the direct. Exact directions for accomplishing this most economically, are difficult to formulate because of the uncertainty in the large number of contributing conditions.

Braestrup[7] has shown for a 20×20-cm irradiated field on wax, that the scattering at right angles to the beam is about 2/10 percent of the dosage rate of the primary beam, and decreases with decrease in field size. It is reasonable to expect that at lower voltages the scattering ratio will not increase, and although the amount of scattering will increase at higher voltages it will take place at a smaller angle to the direct beam, so that the scattering ratio at right angles to the

TABLE IV. *Cost of concrete walls and floors.*

1	2	3	4	5	6
VOLTAGE	THICKNESS		COST/FT.² WALL*	COST/FT.² FLOOR*	COST/FT.² CONCRETE BLOCK†
kv	cm	in.			
100	12.0	4¾	$0.63	$0.38	$0.56
200	22.0	8½	.72	.47	.65
300	24.0	9½	.77	.52	.70
400	26.0	10¼	.79	.54	.73
1000	(30.0)	(12)	.84	.59	.80

* Installed during building construction.
† Installed in completed building.
( ) Extrapolated values.

beam will probably not exceed that for 200 kv. Therefore, if we allow a somewhat generous safety factor, a scattering ratio of 1 percent may be used as a basis for calculating the protection to be provided against the scattered radiation.

Below 200 kv, the decrease in penetration of the scattered, compared with the direct, radiation is not very great, nor are very considerable lead economies to be made by any ordinary means. However, above 200 kv the quality changes are more marked and the possible savings are greater by whatever means achieved.

The wave-length of the scattered radiation at the higher voltages may be computed with sufficient accuracy for our purpose by means of Compton's simple scattering formula $\lambda_\theta - \lambda_0 = \Delta\lambda = 0.0243(1-\cos\theta)$ where λ_0 and λ_θ are the wave-lengths of the incident and scattered radiation, respectively, and θ is the angle between the direct

TABLE V. *Lead equivalents of various building materials.*

1	2	3	4	5	6	7
				BARIUM CONCRETE†		
KV	LEAD	CONCRETE* $\rho=2.4$	CONCRETE BLOCK* $\rho=2.05$	$\rho=3.2$	$\rho=2.7$	BRICK†
	mm	mm	mm	mm	mm	mm
75	1.0	80	85	15	—	175
150	2.5	210	220	28	52	290
200	4.	220	245	60	100	430
300	9.	240	275	105	150	425
400	15.	260	290	140	185	450
‡ gamma-rays	50	(242)	(270)	200	225	—
	100	(480)	(540)	400	450	—

* Taken from Singer, Taylor and Charlton.
† Taken from Kaye, Binks and Bell.
‡ For quantity of radium see Table III.
( ) Calculated values.
ρ = density.

and scattered beam ($\cos\theta=0$ at 90°). Table VI gives, for a number of excitation voltages, the minimum wave-length of the primary beam (col. 2) and the 90° scattered beam (col. 3) and the voltage equivalent to the minimum wave-length of the scattered radiation (col. 4). The possible effect of pair production is neglected. When computing therefore, the lead barriers for scattered radiation, the absorption of the lead is to be taken from the curves at the voltage corresponding to that of the scattered radiation and not the direct radiation.

Protective barriers close to the target, have particular value in the case of supervoltage radiation—above 400 kv—where immense quantities of protective material would be required if

TABLE VI. *Minimum wave-length and equivalent voltage of x-rays scattered at 90°.*

1	2	3	4
EXCITATION VOLTAGE	λ MIN. (PRIMARY)	λ MIN. (SCATTERED)	EQUIVALENT VOLTAGE
kv	A	A	kv
100	0.1234	0.1477	84
200	.0617	.0860	144
300	.0412	.0655	189
400	.0309	.0552	222
510	.0243	.0486	255
1000	.0123	.0365	340
1500	.0081	.0324	380

applied merely to the walls of a room. At excitations in the region of 1000 kv the target is usually at the end of a tube which has a length 5–10 times its diameter. By surrounding the target tube with some 3 inches of lead (the required amounts are not yet known exactly) the escape of radiation is limited to the useful treatment beam and a useless beam directed back along the axis of the x-ray tube. By giving some consideration to the direction of these beams it is possible to design an installation in which all radiation striking a protective wall will have been scattered one or more times through a total angle of at least 90°. The scattered radiation is thereby reduced to a hardness in accordance with Table VI, which requires relatively less protection.

Protection at Excitations Below 100 kv

The problem of protection below 100 kv is relatively simple and needs almost no discussion beyond that given in Handbook 20. For protection against a direct beam, lead thicknesses up to 1.5 mm are sufficient and a 50-percent reduction in thickness leads to no great saving. In this region protection by brick, barium plaster, etc., finds considerable application. Table VII gives the lead equivalents for several of the common construction materials at different low voltages. These are taken from Kaye.[8]

TABLE VII. *Lead equivalents of protective materials at low voltages.*

1	2	3	4	5
		LEAD EQUIVALENTS		
EXCITATION VOLTAGE	RECOMMENDED LEAD	BA. PLASTER* =3.5 G/CC	CONCRETE =2.1 G/CC	BRICK =1.5 G/CC
kv	mm	mm	mm	mm
50	0.5	4	50	80
100	1.5	7	100	200
150	2.5	24	175	400

* 2 parts coarse $BaSO_4$, 2 parts fine $BaSO_4$, 1 part cement.

From this table it is seen that up to 100 kv any of the materials listed will provide adequate protection without introducing constructional difficulties. A 200-mm (8-inch) brick wall should suffice, but care must be taken to insure completely filled mortar joints. At 150 kv about 1 inch of barium plaster is required and difficulties may be encountered because of its weight (16.7 lb./ft.^{2} as compared with 5.9 lb./ft.^{2} for lead) and mode of application. Brick at this voltage is not desirable because of the excessive thickness required. Lead or concrete appear the more logical materials.

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Radium Protection

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IT IS well known that individuals exposed to radium radiations over a period of time may experience serious injuries, even when the intensity of the radiation is very low. With higher intensities, damage may be done in relatively short periods.

In hospitals, where considerable quantities of radium are used in therapy, these dangers are recognized, and steps taken to provide adequate protection. In experimental laboratories, on the other hand, and particularly in some cases of students pursuing work for the Ph.D. degree, such precautions are all too frequently ignored, or only partially followed out. There appears to be a feeling that the period of exposure will be short—a few hours a day or a week, for a few months or a year or two—and that it is unnecessary, and even rather *infra dig*, to bother about protection. It is in the hope of dispelling this idea, and providing definite information on the subject, that this article is written. Data regarding tolerance doses and protective media herein set forth are those which have the approval of the United States National Bureau of Standards, the National Physical Laboratory of England, and the International X-Ray and Radium Protection Commission of the Fifth International Congress of Radiology, and their publications have been freely drawn upon.

Dangers from radium radiations are of two sorts, local and systemic. Local damage is readily inflicted on the fingers, if radioactive preparations are handled carelessly. *No such preparation should ever be touched with the fingers.* Tubes or other containers should be manipulated with forceps or other special handles. The inverse square law is of great importance in reducing the possibility of injurious irradiation. Ten milligrams of radium, or ten millicuries of radon, in a small tube thin enough to permit the escape of most of the beta-rays, at a distance of 3 mm from the skin, will deliver enough radiation to produce a sharp reaction in 10 minutes exposure; at a distance of 10 cm it would require about 1000 times as long. If the radium or radon is screened so that only the gamma-radiation escapes, then the time of exposure to produce a sharp reaction at 3 mm is about 5 hours for 10 mg (50 mg-hr.). In comparison with these periods, even with the 10 minutes for the beta-rays, it may seem that a single picking up and moving a moderately weak source is of no consequence. But it is practically never a single occurrence, and it must be borne in mind that the effect of the irradiation is accumulative, so that one or two contacts a day might soon amount to a dangerous level. It is true that this accumulation is not complete; some recovery takes place in the tissues between exposures. However, this recovery becomes relatively less as the tissues become more damaged.

The *local effects* of radiation manifest themselves first as a reddening of the skin, near the nails, of the fingers which receive the greatest exposure. Later the nails become brittle and tend to crack; the skin at the ends of the index finger and thumb (and possibly others) becomes thick and leathery. Some pain is present, particularly on exposure to heat or cold. Cuts and scratches do not heal well. Warty growths appear, which may become ulcerated and infected, and which may eventually degenerate into cancer.

The appearance of the earliest of these changes should be a warning. It is probable that the development of a slightly red and shiny appearance of the skin at the nails after several months of work need not require immediate cessation of the usual exposure. It should, however, be an indication for added precautions, unless the experiment in hand is almost completed and further irradiation is not contemplated for some time.

In protection from local effects, all three types of radiations from radioactive substances (alpha, beta and gamma) must be considered. Alpha-ra-

exposure, however, is seldom serious. These rays are readily stopped by almost any container in which the material is placed, unless it has been especially designed to allow them to escape. In the case of alpha-ray experiments, contact with or close approach to the source must be scrupulously avoided. In the preparation of polonium sources, great care must be exercised not to get any of the radioactive solution on the hands. If such an accident should happen, immediate and thorough washing is imperative.

The beta- and gamma-rays to be considered in this paper are only those from naturally radioactive substances.* All of the natural beta-rays are stopped by 2 mm of copper, brass, or iron, by 1 mm of lead or silver, or by ½ mm of gold or platinum. Only a very small percentage of them can penetrate more than a centimeter in tissue. The radiation emerging from a lightly screened radium or radon source (in equilibrium with its products) is predominantly beta, only a few per-cent being gamma. If the beta-radiation is not desired in the experiments, it is advisable to enclose the radioactive material in a metal container of sufficient thickness to absorb all of it. If beta-radiation is desired, then all preparations should be handled with forceps at least 20 cm long, preferably provided with a shield of ½ mm of lead, of the general shape of that on a fencing foil. All manipulations and experiments should be carried out, as far as possible, behind lead blocks or screens. (This precaution is necessary in any case, for protection against systemic irradiation by gamma-rays. See below.)

Even when all the primary beta-radiation is eliminated, forceps should always be used in handling radioactive preparations. It should be remembered that secondary beta-radiation is emitted from the surface of any metal container. Moreover, even for weak gamma-ray sources, a damaging cumulative effect will be produced in the skin of the fingers after repeated actual contacts totaling possibly only an hour or two, for a 10-mg source. With ordinary care of this sort in manipulation, local damage is not likely to be a serious problem with gamma-rays, since at distances of a few centimeters the exposures necessary to produce skin reactions are high (approximately 20,000 mg-hr. at 10 cm).

The first symptoms of *general* or *systemic injury* due to over-exposure are a lowered vitality, with a general feeling of lassitude, and frequent headaches. If the exposure continues, sterility may be produced, and also changes in the blood picture, which later may progress to fatal anemia or leukemia. The amount of whole body radiation which can be tolerated before such changes set in is not known. The only means of determining a safe dose for such exposure is to find out the amount of radiation which has been endured without evidence of injury, over long periods, by workers in institutions employing a considerable amount of radioactive material. All the present protection recommendations are based on the results of such observations.

The presence or absence of local effect on the fingers is not a criterion of whether the safe total body dose is exceeded. A careless operator may experience skin changes when the body dose is completely safe. On the other hand, a careful and skillful manipulator may show no skin changes, although his general protection is insufficient.

Checks on the blood count are generally advised, for radiation workers. It is always desirable to have one count (or preferably two or three) made before radiation work is commenced, and others at intervals subsequently. When practicable, they should be made by the same technician, at the same time of day, and employing the same methods. Normal fluctuations in both red and white cell counts are considerable. However, a steady downward trend in either is a danger signal. If it is felt that undesirable changes are occurring, blood counts should be closely watched by a physician with experience in such matters.

There is little danger of systemic damage from either alpha- or beta-rays, since both are non-penetrating. Therefore in the question of general protection, only gamma-radiation need be considered. Moreover, protection against gamma-rays automatically protects against the less penetrating types.

Two aspects of general irradiation must be guarded against: (1) the relatively intense ex-

* Protection from the extremely penetrating beta- and gamma-rays arising in some artificially radioactive disintegrations will be discussed in a subsequent paper by Aebersold.

posures, of short duration, experienced while the operator is actually manipulating the radioactive source or the apparatus near it, and (2) the relatively weak exposures of long duration experienced by anyone carrying on any activity in the neighborhood of the radium.

For safety in the first case, it is necessary to keep the time of such exposures as short as possible. In addition, whenever practicable, a lead screen should be interposed between the radium and the body, of such a size that the worker can reach around it to make necessary manipulations. This may not be thick enough to reduce the intensity of the direct radiation to the safety level, but still be a considerable improvement over no screen at all.

In general the dangers from these short, and relatively intense exposures are not so great as those from the long continued irradiation of low intensity, although they are more likely to be taken cognizance of. Accordingly protection against the latter type of irradiation will be considered in detail. The data to be presented can be used for either case.

It should be pointed out that situations may arise when danger of over-exposure to gamma-rays is greater for an "innocent bystander" than for the individual actually employing the radioactive material. In planning gamma-ray protection, the occupants of rooms above, below, and on all sides of the radioactive material must be considered. An experiment set up and left alone in a room may be considered to need no protection, because no one is in the room with it, when actually someone working steadily at a desk just beyond the wall in the next room may be receiving radiation well above the tolerance dose.

The unit of radiation quantity, the roentgen, and the tolerance dose for x-rays, have been discussed in a previous paper by Taylor. The gamma-ray tolerance dose is assumed to be the same as that for x-rays, about 1 roentgen a week. Some authors consider this dose too large for continuous exposure; it is probably entirely safe for workers in university laboratories or analogous positions. Data given in the following paragraphs are based on approximately such exposures.

As mentioned above, the inverse square law is a powerful adjunct to gamma-ray protection. However, in addition to remaining as far as possible from the radioactive material, it is usually necessary to have a certain amount of absorbing material in the path of the rays. Lead is generally employed for this purpose, because of its density. The chart of Fig. 1, due to Failla, shows the combinations of distance and lead screening necessary for adequate protection for amounts of radium from 1 to 1000 mg.*

As an example of the use of this chart, suppose the amount of radium involved to be 50 mg. For safety in immediate proximity to this quantity, it is necessary to employ 11 cm of lead. However, at a distance of 1 meter, 2 cm of lead is sufficient. If a distance of 2 meters can be maintained, except for brief times necessary to make adjustments in the experiment, no extra lead is necessary. The amount of lead required is not proportional to the amount of radium. For instance, 500 mg requires only 4 cm more lead than 50 mg; namely, 15 cm for contact with the

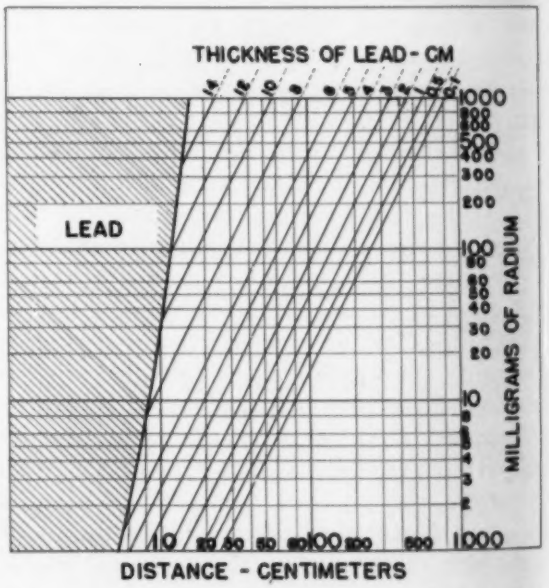

FIG. 1. Chart showing combinations of distance and lead filter for adequate protection from amounts of radium from 1 to 1000 mg. (Failla.)

* This is only a portion of the original chart. For greater or smaller quantities of radium, the reader is referred to the complete chart as published in the National Bureau of Standards Handbook H 23. This can be obtained from the Superintendent of Documents, Washington, D. C., for ten cents, and contains a great deal of detailed information which cannot be included in the present paper.

screen. At 2 meters this amount requires about 3.5 cm of lead; it is not safe to dispense with extra screening unless a distance of 6 meters can be maintained. The data of this chart, and the examples thus far cited, are based on an exposure of 8 hours daily. If the exposure is only half of this, twice the intensity can be tolerated. The protection necessary for any exposure except the eight-hour one cannot be obtained from this chart; it is constructed for this specific rate of irradiation. However, for approximations to the amount of protection required for shorter

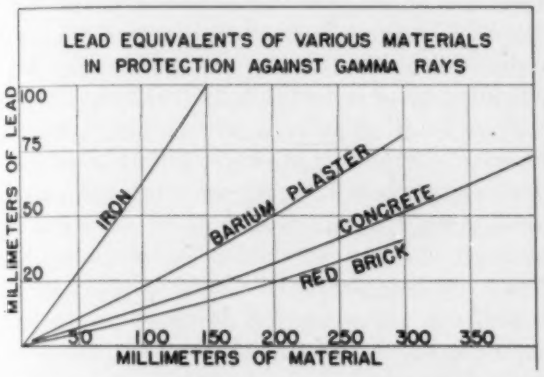

FIG. 2. Curves showing lead protective equivalents of various building materials in the gamma-ray region. (Kaye, Binks and Bell.)

exposures, it may be assumed that what will protect from 100 mg for 8 hours, will protect from 800 mg for one hour, etc.

For complete protective enclosures placed close to the radioactive material, it is preferable to employ lead. However, when the question of protecting individuals in rooms adjacent to the laboratory arises, it is frequently desirable to employ standard building materials. For instance, 250 mg of radium at 3 meters distance requires about 1 cm of lead for protection. It may be that within this 3-meter distance, but in another room, office employees are constantly at work. To cover the wall with 1 cm of lead might be less desirable than to build up a concrete shield. Fig. 2 gives data (due to Kaye, Binks and Bell) for the lead equivalents of certain building materials, in gamma-ray protection. From this it appears that 4½ cm of barium plaster, or 6 cm of concrete would supply the desired protection.* If the existing wall

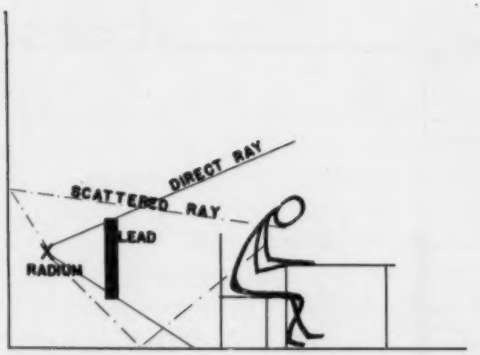

FIG. 3. Diagram illustrating danger of exposure to scattered radiation, when the protective enclosure is not complete.

were 10 cm of brick, that alone would furnish the requisite barrier.

It should be remembered that protection is necessary not only for the direct beam, but also for the scattered radiation. It is not sufficient simply to interpose a lead screen between the radium and the workers in its vicinity. Such a screen might eliminate all the direct radiation, and yet a dangerous dose be scattered back into the room from the walls and floor, as illustrated in Fig. 3. The radium must be sufficiently enclosed on all sides, or else workers must remain at such a distance that the minimum possible path for scattered radiation (or rather, the total distance from the source to the scattering wall and back to the worker) is as great as the safe distance with no extra filter.

If the radium is against an outside wall, it is usually not necessary to enclose it on that side; in an outside corner, two or three sides may be unguarded, if adequate protection is provided on all other sides and carried to these walls. However the possibility must always be investigated of radiation undergoing multiple scattering within the walls, and finally arriving within the room (Fig. 4). Such multiply scattered radiation is, of course, filtered during its oblique passage through the wall, and is, in addition, less penetrating than the primary beam, because of the Compton effect. A small amount of additional filter extending beyond the completely protected enclosure, as in the figure, is sufficient to eliminate it.

* Barium plaster is composed of 2 parts coarse barium sulfate, 2 parts fine barium sulfate, one part cement, or of equal parts of these three materials. Concrete is composed of 2 parts ballast, 2 parts sand, 1 part cement.

FIG. 4. Diagram illustrating need of protection from radiation scattered back within walls.

Adequate storage should be provided for all radium when it is not in use. Such storage should be as remote as practicable from occupied parts of the building. Protection must be provided in accordance with the data of Fig. 1, account being taken of the time during which any individual may be exposed.

Carriers for transporting radium within an institution should be lead-lined and provided with long handles, so that the radium is kept away from the body. For amounts up to 100 mg, a lead lining of 1 cm, and a 50-cm handle provide ample protection without undue weight.

It is always advisable to test the protection for any specific locality, or for an individual working in the neighborhood of radium preparations. Although an effort has been made to comply with safety requirements, it is difficult to be certain that there are no unsuspected leaks. Convenient ionization instruments for making such tests are on the market. They should not indicate ionization corresponding to more than 1 roentgen in a week.

If such an instrument is not available, photographic films may be fixed in various positions in the laboratory, and carried by the personnel. Ordinary dental x-ray films are satisfactory; it is advisable to put a paper clip across the film packet. If the film, developed after two weeks of exposure, is decidedly dark, it is an indication of an undesirable amount of radiation. If the region under the paper clip is not dark, the radiation effective was quite soft, possibly beta-rays. If the film in question was worn or carried by someone, his activities should be checked to see that he is not getting too much local effect in some manipulation. It is a good idea for an active radiation worker to carry several films in different pockets, at different body levels, and rear as well as front. If after a week of exposure and standard development, none of the films is so dark that, when it is put on a printed page in good light, the letters cannot be distinguished through it, then protection is adequate. If a film from one part of the body is much darker than from the others, it is certain that local exposure has occurred. This may not mean that general protection is inadequate, but it calls for investigation.

For more specific information regarding methods of handling and caring for radioactive materials, and for details of protection not discussed in this paper, the reader is referred to the publications listed below. In any particular case, if there is uncertainty regarding the adequacy of protection, and the work is to continue for an appreciable time, it is important to obtain competent advice.

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Resumés of Recent Research

Electron Diffraction Studies of Thin Films Diffusion of atoms upon surfaces has been deduced from measurements of resistance of extremely thin metal films, from thermionic and photoelectric measurements upon composite surfaces, and from optical observations. Recently reported electron diffraction investigations[1] of very thin films have demonstrated that this method of experimentation affords still another means of studying migration of atoms and molecules upon surfaces. It has been discovered by electron diffraction that atoms of a number of different metals, and molecules of a number of ionic compounds, are stable upon a supporting surface of an organic material at temperatures not greatly above room temperature only when drawn together into crystals of appreciable size.

These conclusions were reached from determinations by electron diffraction of mean crystal size and shape in films of known average thickness. The films were prepared by vaporization of weighed amounts of material upon very thin foils of an organic plastic. A beam of electrons passed through a foil and the substance deposited upon it gives a diffraction pattern from which mean crystal dimensions, or at least lower limits, can be determined. Patterns were obtained from many films of average thickness no greater than that of a simple layer of atoms or molecules. These patterns, as well as others, are characteristic of relatively large three-dimensional crystals, proving that the atoms were able to move over the supporting surface and were stable only in crystals of considerable size.

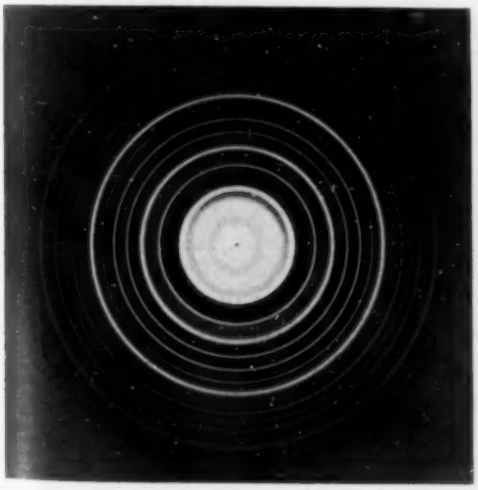

FIG. 1. Electron-diffraction pattern from a caesium iodide film of 30A mean thickness.

[1] L. H. Germer, Phys. Rev. **56**, 58 (1939).

In some cases diffraction patterns from films that were not freshly prepared differed markedly from those produced by the same films at an earlier time. Such differences are attributable to corrosion or chemical change of the films, and in some cases can yield quantitative data regarding such change.

New Presentation of Dilemma of Natural Constants We are so accustomed to taking for granted a knowledge of the fundamental constants, e the electronic charge, m the electronic mass and h Planck's quantum of action that the existence of a serious uncertainty regarding these foundation stones of modern physics is scarcely realized save by the very few who have turned their attention to it.[1]

Of the three constants named, e is the only one which can be measured directly with precision without involving the other two. In general, however, each type of experiment can be regarded as a measurement of a numerical constant A_i which is equal to some product function of e, m and h, i.e., $A_i = e^p m^q h^r$. (For the direct measurement of e we have evidently $p=1$, $q=0$, $r=0$.) Some fourteen such experiments can be classified into nine types according to the function of e, m and h determined. With three unknowns and nine equations one is tempted to

[1] This flaw was first noted by that most reliable of authorities R. T. Birge, Phys. Rev. **48**, 918 (1935). The British physicist H. R. Robinson has referred to it paraphrasing a famous predecessor as "a cloud over the atomic constants." It is not to be confused with the erstwhile supposed disaccord between the old oil drop value of e and the "x-ray" value of e. The present note is a brief resumé of a longer article by J. W. M. DuMond in the July 15 issue of the *Physical Review* (**56**, 153 (1939)). The reader is referred to that article for an extensive list of references here omitted for brevity.

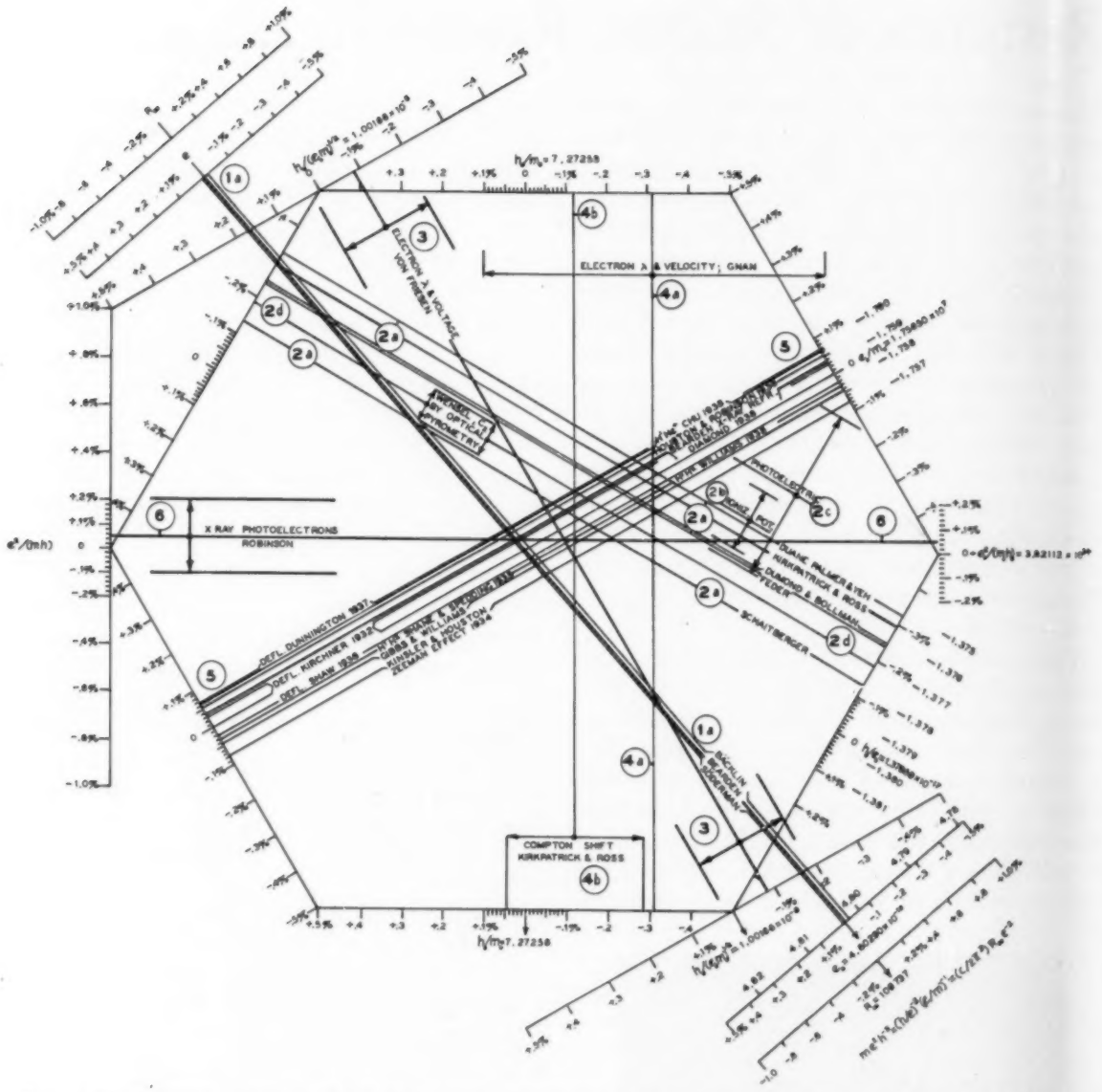

FIG. 1. The dilemma as to the values of the natural constants e, m, and h presented here in a new graphical way. The reference numbers refer to an article in the July 15th issue of the *Physical Review*.

think there exists considerable overdetermination. Indeed the discrepancy in question consists in just this that four of these equations[2] whose constants have been repeatedly and independently determined by many workers in many parts of the world fail to form a consistent set of simultaneous equations to a degree uncomfortably exceeding expectations based either on individual estimates of accuracy or agreement in a given experiment between independent results. The particular nature of the equations however yields less over-determination than one might at first expect since many of them can be expressed as functions of *ratios* of the natural constants. A graphical representation which will permit a clear insight into this tangle of determinations—something that "will spread all the cards on the table" in the clearest and most

[2] The direct "x-ray" determinations of e, the measurements of h/e by means of the short wave limit of the continuous x-ray spectrum, the measurements of e/m and the measurements of the Rydberg fundamental wave number R_∞ equated to Bohr's formula are the four.

unambiguous way is greatly to be desired as a first step in finding advantageous points of attack.

A new and very direct way of doing this has been devised at the California Institute of Technology by J. W. M. DuMond.[3] The new type of diagram is an isometric projection of a Cartesian coordinate system whose axes represent the relative deviations of e, m and h from conventionally adopted origin values. Variously orientated planes in this space represent the different experimental determinations of functions of e, m and h, the origin distance of the plane standing for the relative departure of that experimental result from the origin value and the orientation reflecting the powers in the function determined. This method of discussion brings out, apparently for the first time, the absolute geometric property that of the seven most reliable experiments five *have planes parallel to a common axis*. Borrowing a term from crystal structure these five are called the "cozonal" set. Though there are seven equations it thus appears that to solve for e, m and h with this set either the directly determined e equation or alternately the Bohr equation for the Rydberg constant is indispensable. The new diagram is a projection looking along the cozonal axis so that the cozonal planes are seen on edge as lines. Other planes are brought into the same projection with the help of the Rydberg relation. Fig. 1 shows the chart obtained in this way.[4] In preparing this chart DuMond has tried to avoid as far as possible burying any pertinent information under weighted averages so that most of the reliable determinations appear seaprately on the diagram. After the analysis and rejection of several hypotheses as to the origin of the discrepancy the conclusion is drawn that experiments leading to the determination of h/e should receive careful attention.

[3] The ingenious Birge-Bond diagram which has served so usefully in the penetrating analyses of R. T. Birge on this subject possesess certain disadvantages as to clarity, symmetry of treatment and directness which are avoided in the new graph. A diagram bearing some resemblance to DuMond's but which does not take advantage of the cozonal property was independently devised by R. A. Beth.

[4] In DuMond's article several needed revisions and additions were brought to the author's attention too late to change the cut. These could only be referred to in notes added to proof. In the present note however these changes and additions have been incorporated on the diagram itself.

Separation of Isotopes by Thermal Diffusion Without benefit of theory Soret discovered 60 years ago that the lighter constituents of a liquid solution often become enriched at the top of the solution if this is kept hotter than the bottom. That the same thing happens in gaseous mixtures was not found until 38 years later, after Chapman and also Enskog had predicted the effect theoretically. The general transport theory used for this prediction is complicated and difficult. Indeed, Maxwell missed discovery of the effect because of an assumption he introduced for simplification—that the law of force between the molecules is the inverse fifth power—and this assumption was considered by Boltzmann as an important step in advance.

Last year Clusius and Dickel reported an apparatus for making accumulative the separation of gases (or of liquids) by this so-called *thermal diffusion*, so that in a meter of length from 30 to 50 times the effect of a single unit can be obtained. They have applied this successfully to the separation of the isotopes 35 and 37 of chlorine by thermal diffusion of hydrogen chloride.

These effects have been consistently ignored in the textbooks, perhaps because no simple explanation was available.

In a recent paper[1] elementary principles of simple kinetic theory, as taught to all students of physics or physical chemistry, are combined by the use of elementary mathematics to derive equations for the separation of gases by thermal diffusion (in a single unit). The equation for binary mixtures has been tested by available data and found to give an upper limit: in some cases the limit agrees with the experiment and in the worst cases is about double the experimental value.

An equation for the separation of gases in mixtures of any number of species shows that the relative separation of two heavier gases should be increased by the addition of a lighter gas. No experiments are available for testing this. If it is borne out by experiment it ought to be of considerable practical importance in the separation of isotopes.

No valid theory, simple of complex, appears to be available for the case or liquid solutions.

[1] L. J. Gillespie, J. Chem. Phys. **7**, 530 (1939).

Uranium and Atomic Power

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Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
AND
J. B. H. KUPER,
Washington Biophysical Institute, Washington, D. C.

Can the energy which is locked up in the nuclei of atoms be made available for everyday use? Dr. Roberts and Dr. Kuper in this article analyze the possibilities at the present time.

ON the basis of the equivalence of mass and energy (through the relation $E=mc^2$) there has been much speculation concerning the possibility of releasing atomic energy to furnish a new source of power. Hopes of attaining this goal were briefly aroused when Cockroft and Walton published their first experiments in nuclear disintegration in which they obtained alpha-particles with energies of 8 Mev (million electron volts) from the bombardment of lithium by protons of relatively low energy. However, it was soon realized that this reaction would never furnish a source of power as the yield of alpha-particles was far too low.

This subject was recently reopened by the striking discovery of the "fission" of uranium announced by Hahn and Strassmann in Germany. They found, by a series of chemical analyses, that the unstable atoms observed after the bombardment of uranium by neutrons were not elements beyond uranium in the periodic table, but were really radioactive isotopes of known elements such as barium, cerium, and lanthanum. Almost immediately, Meitner and Frisch interpreted these results to mean that the uranium nucleus, after being struck by a neutron, split into two large fragments with the liberation of about 200 Mev (3.2×10^{-4} erg). These high energy fragments were soon observed directly and found to be particles with masses of approximately 100 and 140 units. It was also found that neutrons were emitted along with the heavier fission-particles, and the question at once arose as to whether these neutrons were sufficiently numerous to make possible a chain-reaction in which uranium is "burned" to furnish power.

In spite of the intensive work on this process in laboratories both here and abroad, there are not yet sufficient data to say definitely whether or not a uranium power-house is a possibility. These notes are presented in response to an expressed need for a review of the facts known at present, from which the reader may draw his own conclusions.

The most efficient nuclear reaction known requires the expenditure of about 3000 Mev to produce one neutron. Hence the possibility of obtaining atomic power from uranium fission hinges on the liberation of sufficient numbers of neutrons in the fission process itself to maintain a regenerative reaction. Both fast neutrons (with energies greater than 0.5 Mev) and very slow neutrons (with thermal energies, roughly 1/40 electron-volt) are effective in producing uranium fission. Also there is a strong resonance absorption band, one ev wide, with an extremely large cross section* at 25 ev. This resonance results in the formation of U^{239} by radiative capture. U^{239} is a beta-emitter which presumably transforms to element No. 93. Neutrons absorbed by this resonance-capture are effectively lost with regard to power-production. The cross section for fission by fast neutrons rises very rapidly with neutron-energy between 0.5 and 2 Mev and does not increase much beyond that point. The fission cross section for thermal neutrons is some 40 times larger than the maximum cross section for fast neutrons.

The energy distribution of the neutrons released in fission is not well known as yet. Energies

* Absorption coefficient per atom for a given process.

as high as 11 Mev have been reported and more reliable evidence shows neutrons with energies greater than 2 Mev. There are also indications that lower energy neutrons are much more numerous and that the average energy does not greatly exceed one Mev.

The number of neutrons emitted per fission has been measured by several different methods which agree reasonably well. These estimates range from 1.5 to 3.5 and it would seem at first sight that the requisite conditions for a chain reaction were satisfied. However, the probability of scattering is more than 100 times greater than the probability of fission production for one-Mev neutrons. The energy loss in the numerous collisions which do not cause fissions rapidly reduces the probability of a subsequent fast neutron fission process, and it seems very unlikely that the fast neutrons can produce a sufficient number of fissions to maintain a regenerative reaction. This possibility cannot definitely be excluded for very large quantities of pure uranium, but dilution of the uranium by hydrogen would definitely prevent any multiplication of this sort.

At present dilution by hydrogen seems to be the most promising approach. Thermal neutrons are many times more effective than fast neutrons for fission-production, but a difficulty is encountered in slowing the initial fast neutrons to thermal velocities without loss through absorption in the resonance at 25 ev or in other processes now unknown. Since uranium is very heavy it is relatively ineffective in absorbing energy by collision. The majority of the neutrons would not reach thermal energies by slowing down in pure uranium since they would make many collisions while in the resonance region and consequently would be absorbed. To avoid this predicament it has been suggested that the uranium be diluted with some material containing hydrogen. In such a medium it would be possible for the neutrons to "jump over" the resonance-region as they lose a large share of their energy in each hydrogen collision. This would of course entail the loss of more neutrons by absorption in the added material.

Even for thermal neutrons radiative capture leading to U^{239}, as in the 25-volt process, competes with the fission process, but present evidence indicates that more than one neutron is emitted per *thermal* neutron absorbed in *uranium*. This means that a chain reaction would be possible if all the initial neutrons could be brought to thermal energies and if there was no absorption by anything but uranium. Unfortunately for those who would use uranium power this is not the case. The absorption of water is extremely important if sufficient water is used to avoid undue loss by resonance capture in uranium. There is no indication as yet that, even with the most favorable uranium-water mixture, the number of neutrons emitted per neutron absorbed by *all processes* would be greater than one. In any event several hundred tons of uranium would be necessary to reduce sufficiently the loss of neutrons through the walls of the reaction vessel so that a chain could maintain itself.

So far it has been possible to speak of uranium without considering which of its isotopes is concerned in the various processes. The calculation of the energy evolved per gram of uranium "burned" depends to a great extent on the isotope responsible. The two principal isotopes of uranium have atomic masses of 238 and 235, the isotope of mass 238 being 139 times more abundant. Both the resonance capture and the fast neutron fission process are ascribed to U^{238} because of the large cross sections observed for these processes. If the rarer isotope were responsible in these cases the actual cross sections would be 139 times larger than those measured, which seems most unlikely in view of other information about nuclear processes. The thermal-neutron fission-process can be tentatively ascribed to U^{235} for two reasons. First, it seems unlikely that the same nucleus should show a sharp resonance for capture as well as a fission-process for thermal neutrons. Secondly, the rapid increase of the probability of fission by fast neutrons in the region 0.5 to 2 Mev indicates that a certain minimum neutron energy is necessary to produce the effect. Since these two processes, already ascribed to U^{238}, seem to preclude any fission by thermal neutrons in the same nucleus it is necessary to assume that the next most abundant isotope U^{235} is responsible for the thermal fissions. The definite proof of this hypothesis must wait for the separation of

sufficient quantities of one isotope for direct experiments.

Assuming that U^{235} would be the active ingredient if a chain reaction should be possible, we find that uranium has no very great economic advantage over coal. The energy released per atom of uranium "burned" is 200 Mev as compared to four ev for coal. This enormous ratio must be divided by 20 and again by 139 to compare these "fuels" in terms of energy per gram, and the ratio becomes 17,000. Uranium oxide (96 percent pure) sells for approximately $2 per pound which is roughly equal to the price of a ton of coal at the mine. In terms of energy per dollar uranium is cheaper by a factor of 8.5. Should there be a demand for uranium as a fuel the price would undoubtedly increase. Further refinement would presumably be necessary and increased use would exhaust the limited reserves of high grade ore. If uranium were to replace the 500,000,000 tons of coal used annually in this country the amount of uranium consumed would increase 15,000 per cent.

The present situation is that a chain reaction cannot be ruled out definitely for either fast or slow neutrons, but that there is no evidence of any kind that such a reaction will really occur. The possibility of using other elements has already been explored. Thorium is the only other element which shows fission and it is at least five times less efficient than uranium. The slow neutron process in uranium seems to be the most promising and would probably work if the content of U^{235} could be enriched. However, this reaction is less favorable from the economic viewpoint. Undoubtedly, special uses would be found for such a concentrated fuel, but the day of free atomic power is probably not yet in sight.

Advisory Council on Applied Physics

of the

American Institute of Physics

Report of Meeting
Pittsburgh, March 25, 1939

THE meeting was called to order by Chairman Kelly who proceeded to call the roll. The following were present:

Members

CARL L. BAUSCH, *Bausch and Lomb Optical Company*
LEWIS W. CHUBB, *Westinghouse Electric and Manufacturing Company*
WHEELER P. DAVEY, *Research Professor of Physics and Chemistry, Pennsylvania State College*
DONALD W. DUNIPACE, *Libbey-Owens-Ford Glass Company*
SAUL DUSHMAN, *General Electric Company*
HARVEY FLETCHER, *Physical Research Director, Bell Telephone Laboratories*
PAUL D. FOOTE, *Executive Vice President, Gulf Research and Development Company*
JOHN J. GREBE, *The Dow Chemical Company*
L. O. GRONDAHL, *Director of Research and Engineering, Union Switch and Signal Company*
MAURICE HOLLAND, *Director, Division of Industrial and Engineering Research, National Research Council*
M. J. KELLY, *Director of Research, Bell Telephone Laboratories*
JOHN P. MAGOS, *Testing Engineer, Research Testing Laboratory, Crane Company*
E. J. MARTIN, *General Motors Corporation*
ARCHIBALD F. MESTON, *Research Corporation*
H. HUGH WILLIS, *Sperry Gyroscope Company*
HENRY A. BARTON, *Director, American Institute of Physics*

Substitutes

JOHN F. KELLEY, *The Celotex Corporation (for Wallace Waterfall)*

Guests

EDWARD U. CONDON, *Westinghouse Electric and Manufacturing Company*
ELMER HUTCHISSON, *University of Pittsburgh and Journal of Applied Physics*
E. WARD TILLOTSON, *Mellon Institute*
ARCHIE G. WORTHING, *University of Pittsburgh*

I. Chairman's Report

The Chairman recalled the appointment of the Council by the American Institute of Physics in the Fall of 1935 to act in an advisory capacity on matters of policy concerning applied physics. Its first meeting[1] was held in November of that year in connection with a Conference on Industrial Physics at the University of Pittsburgh. The topics of discussion were: the training of physicists for industry, the publication of a book on applied physics which would make physics better known to the general public, and whether or not any further organization was necessary to express properly the needs of applied physicsts. A resolution was passed that in the opinion of the Council the interests of applied physicists for the present could be taken care of best in the various existing organizations of the Societies in the Institute. The Optical Society of America, The Acoustical Society of America, and The Society of Rheology could take care of the applied physicists in the fields of optics, acoustics, and rheology, while the Physical Society could take care of the interests of applied physicists in other fields. It was recommended that the Physical Society appoint a committee to decide how the interests of applied physicists could best be taken care of. This committee was appointed and held informal conferences at Chicago, Detroit, Boston, and Pittsburgh to formulate a definite policy. The committee recommended to the Physical Society that the time was not ripe for the formation of a special division on applied physics. It was recommended that papers in this field be presented at regular meetings of the American Physical Society. It was further recommended that if the Institute developed a sound publication policy the American Physical Society should offer the journal *Physics* to the Institute to be made into an official publication for the applied physicists.

A meeting[2] was held in October, 1936, in New York under the chairmanship of Dr. L. O. Grondahl. At this meeting the initiation of an

[1] Rev. Sci. Inst. **7**, 113 (1936).
[2] J. App. Phys. **8**, 98 (1937).

employment service for physicists by the American Institute of Physics was discussed. Also the plan of the American Institute of Physics to accept the journal *Physics* from the American Physical Society and to carry it forward under a new name—the *Journal of Applied Physics* was discussed. The first issue of this Journal appeared in January, 1937. No meeting of the Advisory Council on Applied Physics was held during 1937.

II. Director's Report

The Chairman then called upon Dr. Henry A. Barton, Director of the American Institute of Physics to report on that organization's activities since the last meeting. Dr. Barton reported approximately as follows:

One of the most important activities of the Institute since the last meeting of the Advisory Council was the sponsorship of a joint meeting of all the member societies of the Institute in New York. This was by far the largest meeting of physicists ever held in America. The meeting drew striking attention to the part which physicists are playing in everyday life. A new interest in physics and in physicists on the part of industry and the general public was aroused. Because of the success of this meeting there is insistent demand to have another such meeting.

There has also been a demand for meetings in special fields of physics. In answer to this demand the Institute has sponsored several special meetings. For instance, in 1937, a meeting on the Physics of Metals was held at Cambridge, Massachusetts, in cooperation with the Massachusetts Institute of Technology with an attendance of approximately 300 people. A meeting was held in Philadelphia on Biophysics in cooperation with the Johnson Foundation for Medical Research at the University of Pennsylvania and its Director, Dr. D. W. Bronk. The attendance at some of the sessions was as high as 800. This meeting was the first to give general recognition to the increasingly important field of biophysics. Another meeting of the same kind was one on Physics in the Automotive Industry held at Ann Arbor in cooperation with the University of Michigan. This meeting brought out clearly the need for physicists in the automotive industry and the progress which comes about by scientific research.

The Placement Service of the American Institute of Physics is now approximately two years old. Through its help a number of physicists have found positions acceptable to them. It is interesting to note that more industrial organizations than universities have made inquiries for men. Considering the difficult general employment situation during the past two years the Institute feels that its Service has been at least moderately successful.

Recently the Institute has been recognized in a fine way by the National Association of Manufacturers. The Institute has cooperated in the arrangement of programs on industrial research for their general meetings and in the publishing of a Science Supplement of the Association's regular News Letter. At the last meeting of the N. A. M. a symposium on "How Can Scientific Research Be Made More Valuable to Industry" was arranged. In this symposium three points of view were given: (1) Willard H. Dow, that of the manufacturer; (2) Isaiah Bowman, that of the universities; and (3) Carl Breer, that of the industrial research laboratories.

A word regarding the general situation of the Institute is in order. The American Institute of Physics, Incorporated, has five societies as members—the American Physical Society, the Acoustical Society of America, the American Association of Physics Teachers, the Optical Society of America, and the Society of Rheology. The Institute has two primary purposes. The first is concerned with publication matters. It assists in the publication of the Societies' journals—*Journal of the Acoustical Society of America*, *The American Physics Teacher*, *Journal of the Optical Society of America*, *The Physical Review*, and the *Reviews of Modern Physics;* it sponsors and publishes three journals in its own name—(1) *The Journal of Chemical Physics* which is entirely an archive journal and which makes a small profit each year, (2) *The Review of Scientific Instruments*, and (3) the *Journal of Applied Physics* both of which are service journals as well as archive journals. In 1937 the last two journals cost the Institute approximately $7,000 and in 1938, $4,000. Much of this expense was in the nature of circulation promotion and would not normaliy recur every year.

The second major activity of the Institute is classified as Organization and Education. This embraces all services jointly to the Societies in their common interests or to the science and profession of physics as a whole. Many questions of policy are referred to suitable committees, special studies are made of publication or other needs, funds are sought for activities or physicists, cooperation is maintained with the National Research Council and other scientific bodies, the Placement Service is operated, a program of dignified publicity is continually carried on, assistance is given to the Societies at meetings and in other respects, special meetings are arranged and many other lesser functions are carried out. The general secretarial, financial and business aspects of physics as a science and profession have been increasingly delegated to the Institute.

The American Institute of Physics is financed by an allowance contributed by the Societies which is determined by taking 15 percent of the publishing costs of the Societies' journals. In 1938 each of the member societies voluntarily raised their allowance to 20 percent temporarily. The Institute also receives income from industrial associates who contribute $175 annually. These companies receive all the Institute's publications so that the net income available for other activities is approximately $120 per associate. At the present time the following companies are associates of the Institute:

Agfa Ansco Corporation
Allegheny Steel Company
Aluminum Company of America
American Telephone and Telegraph Company
Bausch and Lomb Optical Company
Bell Telephone Laboratories
Crane Company
Dow Chemical Company
E. I. duPont deNemours and Company
Eastman Kodak Company
General Electric Company
General Motors Corporation
Gulf Research and Development Company
Libbey-Owens-Ford Glass Company
Loomis Laboratory
Massachusetts Institute of Technology, Department of Physics
Massachusetts Institute of Technology, Division of Industrial Cooperation
Research Corporation
Shell Development Company
Sperry Gyroscope Company, Incorporated
Westinghouse Electric and Manufacturing Company

At the end of 1937 the Institute had a standing deficit of $21,845 which was reduced in 1938 to $20,814. This deficit accumulated during the early years of the formation of the Institute when *The Review of Scientific Instruments* was given to all members of the founder societies free of charge. Every effort is being made to reduce this deficit as quickly as possible, a considerable reduction being budgeted for 1939. When one realizes that there are over 4500 members of these five societies forming the Institute, this deficit does not appear overwhelmingly large. The officers of the Institute are, however, anxious for further suggestions as to how the deficit may be wiped out.

III. The Journal of Applied Physics

Postponing discussion of Dr. Barton's report until later in the meeting, the Chairman called upon Dr. Elmer Hutchisson to report on the editorial policy of the *Journal of Applied Physics*. His report was approximately as follows: The primary purpose of the *Journal of Applied Physics* is to provide papers describing the applications of physics in industry, to provide reviews of topics in general physics which may find application in the future, and to publish research papers in the field of applied physics. This field is so large that a question immediately arises as to the breadth of coverage of such a Journal. If the coverage is narrow a particular reader will find in any issue much that is of interest, but the number of these readers will be so small that the price of the Journal necessarily will be very great. On the other hand if the coverage is large, the number of readers will increase and the cost of the Journal per subscriber will be small but if this procedure is carried too far a point is reached where one is printing, using paper and mailing material which is of no interest to a great number of subscribers. Obviously this procedure is not economical, and a limit to the number of subscribers is reached because such a large fraction of the Journal is of no interest to the general subscriber. Thus an average must be struck in which there are a large number of subscribers and each subscriber

finds a sufficiently large part of the Journal of interest to justify his continuing his subscription.

The part of the Journal which has the most general appeal and is, therefore, most useful in bringing about a desirable number of subscribers is the section of the Journal which contains summaries, reviews, descriptions of industrial laboratories, and similar features. There is a tendency for these general papers to be of a critical rather than of an informative nature. The reason for this is rather obvious. The Journal is unable to pay an honorarium for its papers and the chief compensation for writing papers of this kind comes from the professional attention which these papers receive. There is, therefore, a rather unconscious tendency to write a paper which will appeal to one's colleagues rather than to the general public. A continuous effort must be made on the part of the editor to keep the level of the papers such that they will appeal to a large number of readers. To assist in this plan a new editorial policy has been initiated in 1939. This plan is to appoint a recognized leader in a given field as a guest associate editor and ask him to plan a set of papers to be published in one issue which will cover a field of unusual interest. This associate editor will also help to keep the papers on a suitable level. Experience has shown that it is much easier to induce someone to write a paper at a given level if other specialists in the field are writing papers on a similar level. Following this plan, we have been very fortunate in obtaining a series of papers on the Physics of Television for one of the coming issues. The guest editors who have been appointed are as follows: F. Bitter, Magnetism; W. E. Forsythe, Temperature and Its Measurement; L. A. Jones, Physics of Photography; W. F. Meggers, Spectroscopy; B. E. Warren, Physics of X-Rays; J. B. Whitehead, Insulation and Dielectrics; and V. K. Zworykin, Television.

The initiation of the above plan has brought to the Journal a large number of general papers in addition to those which are normally received. These papers are very much worth while in that they will lead to a wider circulation of the Journal and, therefore, the possibility of a better journal. On the other hand, another difficulty has arisen partly because of the increased number of general articles and partly because of the increased activity in applied physics together with an increasing recognition of the Journal. This difficulty is the impossibility of publishing all the research work in the field of applied physics. In fact manuscripts are received at the rate of about 20 a month and can only be published at the rate of about four a month without exceeding the budget. Such procedure can lead only to a long delay in publication. If such a delay does exist many of the papers automatically will go to other journals. It is unfortunate that this is true since only the poorest will be left with the *Journal of Applied Physics*. However, until the circulation is increased and, therefore, the budget is increased there seems little hope of publishing all the good papers which are received. The editor will appreciate suggestions as to what may be done under these circumstances.

A considerable number of comments were aroused by this report. The question was raised as to how much additional budget would be needed to publish most of the good papers which are submitted. Dr. Hutchisson estimated that in the neighborhood of $4000 per year would be needed. Dr. Foote suggested that some of the other journals do publish most of the papers that are sent to them and that the *Journal of Applied Physics* would ruin its chances of expanding by cutting down on the number of research papers published. He felt that the number of research papers should be increased and that funds should be obtained from industry or some other source. Dr. Kelly suggested that chemical engineering is a more unified field than applied physics and that may be the reason why it is easier to find money to publish papers in chemical engineering. Dr. Dushman suggested that most of the men in industry want surveys of what is happening in branches of physics other than their own and that review papers are most popular. Dr. Meston emphasized that it is also necessary to help research physicists obtain support from their executives. He believed that to do this the general articles must be written so that non-specialists could read them and that if anything more emphasis should be placed on general articles. The general conclusion of the discussion was that the Journal should continue to publish general articles and should publish only

those research papers which it could without exceeding its budget. Before more research papers are published a new source of income would have to be found.

IV. JAP—RSI Questionnaire

Dr. Kelly next reported on a questionnaire which was sent out to determine if possible any modifications in the JAP or the RSI which would obtain the support of a large number of people. When the RSI was placed under the sponsorship of the American Institute of Physics it contained all the advertising of the Institute journals. It was given to all members of associate societies first at no cost and then at a very low cost—decidedly less than it cost to publish it. When the JAP was started it also carried advertising and duplicated the advertising of the RSI. In its second year the JAP carried its own independent advertising section but all the advertising income was used to pay the deficits in both journals. Certain parts of the JAP duplicated similar features of the RSI. To decide whether this duplication was objectionable and to canvass the readers' tastes as to the kind of journal which would have the greatest appeal to the readers, a questionnaire prepared by a committee consisting of G. B. Pegram, M. J. Kelly, and H. A. Barton was sent out. This was sent to 400 subscribers of the RSI alone, 400 of the JAP subscribers alone, 400 who received both journals and 400 who received neither journal. A large number of replies have been received and a preliminary analysis indicates that (1) the two journals could not be combined at the present time without losing subscribers, (2) the interest of the readers in the RSI is primarily in the instrument section, (3) an increase in the subscription price of the RSI to $2.50 would probably lose enough subscribers so that the Journal would not be any better off. As a result no other action is planned during the present year then to restrict the field of the RSI to instrument articles and to decrease the number of pages of other material for the sake of economy. It is thought that eventually the RSI may revert somewhat to its original character; namely, that of an archive journal in the instrument field and that people will be willing to pay enough for it so that it will be self-supporting without advertising other than that of instruments. Dr. Meston inquired as to the kind of articles which seemed most favored for the JAP. Dr. Kelly replied that 60 percent preferred the general articles. Also more subscribers were interested in a journal like the JAP than in a split archive and general service journal. Dr. Chubb indicated that he believed along with Dr. Foote that it was exceedingly important to continue publishing Contributed Original Research articles as fast as possible. There was general agreement with this statement but it was recognized that the papers could not be published any faster than at present without more money.

V. Popular Book on Applied Physics

In the absence of Dr. G. R. Harrison the Chairman asked Dr. Barton to report on the popular book on applied physics which Dr. Harrison is writing at the original suggestion of the Institute. Dr. Barton reported that the book has already been rewritten about five times. It has been referred to both physicists and laymen for criticism. The book itself is intended to appeal to laymen. Several chapters have been published in popular magazines. A chapter entitled "More Precious than Rubies" was published in *Harper's* "When Physics Goes Farming" in the *Atlantic Monthly*, and another article on "Physics in Medicine" will be published in the *Atlantic Monthly*. The book will probably appear in October under the title *Atoms in Action* with the subtitle, "The World of Creative Physics." Besides the chapters mentioned above, there are others on electronics, light, communication, etc. Those which have been published have been most favorably received, justifying confidence that the book will enjoy a large sale. It was suggested that it should be used widely in elementary and high schools.

VI. Future Special Meetings

Dr. Barton reported that preparations are under way for a second joint meeting of all the societies concerned with physics in the Fall of 1941 in New York. The suggestion was made that an unprecedentedly large gathering of physicists, development engineers, physical chemists and others such as would assemble for this meeting would constitute a very desirable audi-

ence for an instrument exhibit. Instrument manufacturers have urged the holding of another joint meeting like that of 1936 and would undoubtedly show some of their products in any case. If the manufacturers wished to enter into full cooperation it might be possible to arrange the finest instrument exhibit ever held. Physicists and those in related fields are naturally greatly interested in instruments and it would be proper to feature the use of instruments in a special section of the general program. Reference was made to the regular exhibiting and cataloguing of British instruments under the auspices of the Physical Society of London. The Institute would not, however, push an instrument exhibit unless it met the very real approval of the manufacturers.

The last joint meeting emphasized particularly the application of physics in industry. A similar central theme is desired for the coming joint meeting. Suggestions as to a theme and as to invited papers will be appreciated.

A symposium on the Measurement of Temperature will be held early in November of 1939. This symposium will be primarily from the point of view of the users of instruments rather than that of the manufacturers of instruments. Some of the engineering societies are informally helping to prepare the program. The meeting will be held in New York. The Institute would appreciate suggestions as to what fields should be considered for further symposia. It is important to consider the place, the manner of cooperation, and the practicability of the meeting. Several suggestions were brought forward. Mr. Grebe suggested that since the Chemical show is scheduled for about December 1, it would be wise to hold the meeting on Temperature Measurement at approximately the same time so that both meetings could be attended at one time. Dr. Worthing suggested that "Instruments" might be the principal theme of the 1941 meeting and invited papers on vacuum pumps, x-ray machines, etc., would be in order. Dr. Davey seconded this idea. Dr. Grebe suggested that "Physical Measurements" be the theme of the 1941 meeting rather than instruments.

Dr. Magos asked whether there was any opportunity for industrial physicists to organize in some way to secure for themselves better professional recognition than they have now. He thought that there was a tremendous potential membership. Dr. Barton reviewed discussion at previous meetings suggesting that these men join the Physical Society and elect to receive the *Journal of Applied Physics*. He suggested that the applied physicists could arrange special programs to be held in connection with the Physical Society meetings. Dr. Grondahl mentioned that this suggestion had been thoroughly considered a few years ago by a committee of the Physical Society and that this committee concluded that it was difficult to find a common ground for an organization of industrial physicists. He believed that the most logical method is to stay with the American Physical Society and arrange special programs at the regular meetings that are of interest to the industrial physicist. Dr. Dushman stated that there are many local Physical Societies which are meeting regularly and which stress the industrial side of physics. He believed that it might be possible to have these men subscribe for the *Journal of Applied Physics*. He suggested that the Physical Society have a section devoted to applied physics at one of its annual meetings to see how it would be received. Dr. Foote suggested that if the meeting is held it should have a separate chairman from the regular Physical Society meeting and that this chairman ought to help arrange the program.

Dr. Grebe mentioned that the ASME has formulated examinations to enable engineers to be registered in various states. Since so many branches of engineering are beginning to require registration, it seems important that the physicist should also formulate an examination which when passed would give a person a legal standing as a physicist. Otherwise all physicists will tend to be called engineers in order to have a legal standing. There was general agreement with this sentiment, and the Chairman promised to appoint a committee for the study of laws and regulations for physicists.

On behalf of the officers and those concerned with the Institute, the Chairman expressed appreciation for the interest and attendance of the members of the Council on Applied Physics at this meeting. The Council then adjourned.

HENRY A. BARTON, *Secretary*

Contributors to This Issue

Samuel G. Eskin graduated from the Massachusetts Institute of Technology in 1926 with the degree of B.S. in mechanical engineering. He has taken graduate courses at M.I.T. in 1935–36 and received the degree of M.S. in physics from the Northwestern University last spring. He was a research and development engineer with the Edison General Electric Appliance Company and is now in charge of research department of the Robertshaw Thermostat Company.

Ronold King was born in Williamstown, Massachusetts, in 1905. He received the A.B. degree (1927), the M.S. degree (1929) from the University of Rochester, the Ph.D. degree (1932) from the University of Wisconsin. In 1928–29 he was American-German Exchange Fellow at Munich; in 1929–30 White Fellow in Physics at Cornell University; in 1930–32 University Fellow in Electrical Engineering at the University of Wisconsin. During 1932–34 he was teaching and research assistant at Wisconsin. The years 1934–37 he was at Lafayette College as Instuctor and Assistant Professor of Physics. The year, 1937–38, he spent in Berlin on a Guggenheim Fellowship. At present he is Assistant Professor of Physics and Communication Engineering at Harvard University.

Photograph and biography of R. E. Holzer appeared in Vol. 9, p. 123, of the February, 1938, *Journal of Applied Physics*.

E. Weber

Everly John Workman received his B.S. in Physics from Whitman College, in 1924 and his Ph.D. from the University of Virginia in 1930. During the next two years he was National Research Fellow at the Bartol Research Foundation of Franklin Institute and California Institute of Technology. The year following he was a Research Associate, Reed College and since 1933 has occupied the position as Professor of Physics and Head of the Physics Department at the University of New Mexico at Albuquerque.

Lewi Tonks has been a research physicist in the Research Laboratory of the General Electric Company at Schenectady since obtaining his Ph.D. from Columbia in 1923. His work has lain mainly in the field of low pressure arcs. He has also made contributions regarding the propagation of large Barkhausen discontinuities of magnetization.

Ernest Weber received his E.E. degree from the Polytechnic Institute of Vienna in 1924 and a year later received his Ph.D. from the University of Vienna. In 1927 he received the degree of Dr. of Technical Sciences from the Polytechnic Institute of Vienna. From 1924 until 1929 he was research engineer at the Oesterreichische Siemens-Schuckert Werke, Vienna. He was Privat-Dozent of Electrical Engineering at the Polytechnic Institute of Berlin in 1929 and the following year came to the Polytechnic Institute of Brooklyn as Visiting Professor of Electrical Engineering. Since 1931 he has been Research Professor of Electrical Engineering at the Polytechnic Institute of Brooklyn.

S. G. Eskin

R. King

E. J. Workman

L. Tonks

New Books

Modern Magnetism. L. F. Bates. Pp. 340+ix, Figs. 97, 14×22 cm. University Press, Cambridge and Macmillan, New York, 1939. Price $4.50.

About one-half of this book is devoted to ferromagnetism, the other half to diamagnetism and paramagnetism and the background of atomic structure necessary for the understanding of the various kinds of magnetic properties.

The greater part consists of a detailed description of experimental methods. This emphasis is illustrated in Chapter III on "Susceptibility Measurements With Isotropic Substances" in which, after 2 pp. of introduction, 32 pp. are given over to an exhaustive account of methods of measuring susceptibilities, and then 8 pp. to a discussion of the results in their relation to theory, a discussion limited to the salts of iron and rare-earth families. The reason for this distribution, as stated by the author in the preface, is a result of his teaching experience in which he finds that the unusual difficulty of students with the subject of magnetism can be alleviated by developing the subject more from an experimental than from a theoretical side.

Although about half the book is devoted to ferromagnetism, very little space is given to magnetic alloys. In fact the whole discussion of the properties of the magnetically soft iron-nickel alloys such as permalloy and the new age-hardening alloys such as alnico, is confined to about 3 pp.

The first chapter (54 pp.) gives an excellent account, with a minimum of mathematics, of the background of atomic structure necessary for magnetism. This includes, the Bohr theory, later developments in quantum theory, spin-orbit coupling, Zeeman effect and multiplet widths. Later chapters (38 pp.) describe the properties of single particles—the moments of molecules, atoms, protons and neutrons as determined from "molecular"-beam experiments. A chapter on gyromagnetic effects (31 pp.) gives an extensive account of the work on both ferromagnetic and paramagnetic substances. In the chapters on ferromagnetism are discussed the Weiss-Heisenberg theory, the specific heat and magnetocaloric effect, magnetostriction and the Barkhausen effect, and magnetic crystals.

The content of a book is sometimes best described by pointing out the things it does not contain. Among the things mentioned briefly (about one page) or not at all are the effects of stress on magnetization, the nature of alternating and rotational hysteresis, a discussion of the form of the technical magnetization curve in low and intermediate fields and its interpretation in terms of the domain theory, powder patterns, and the band picture of the distribution of electrons in various atomic energy levels.

The value of the book lies in its well-written accounts of experimental methods and of the background of atomic theory. Its weakness for the "applied physicist" is its lack of discussion of such important parts of ferromagnetism as hysteresis and the phenomena associated with it, and the properties of alloys.

R. M. Bozorth
Bell Telephone Laboratories

Photographic Chemicals and Solutions. J. I. Crabtree and G. E. Matthews. Pp. 360+viii, Figs. 95, 16×24 cm. The American Photographic Publishing Company, Boston, Massachusetts, 1939. Price $4.00.

This authoritative book, the first extensive treatment of the subject in English, is based largely upon the wide experience of the authors themselves, who have been research chemists with the Eastman Kodak Company for almost 30 and 20 years, respectively.

The completeness with which the work covers the field is indicated by the list of chapter subjects: terminology, arithmetic, apparatus, construction materials, temperature measurement and control, water supply, technique of mixing and processing, high temperature processing, storage and transportation, substitution of chemicals, stains, cleaning the apparatus and the hands and clothing, precautions in handling dangerous chemicals. The appendix includes, among several lists and tables, a useful list of commercial sources for the more special types of apparatus and material, and a formulary, which comprises the representative collection of photographic recipes that has been codified by the Eastman Kodak Company.

While the book is evidently intended as a practical working manual, the authors are to be commended for endowing it with a logical pattern and a clarity* more commonly found in a monograph or a good textbook than in a work so directly utilitarian.

Julian Ellis Mack
University of Wisconsin

* But it is incongruous, in the midst of a clear simple modern exposition of the properties of the alkalis used in photography, to find a mysterious word (Kodalk) representing a secret proprietary chemical which the prospective user is expected to accept on faith without understanding. Undoubtedly the blame for this anachronism should rest, not with the authors, but with a usually progressive manufacturing company, which has in this instance reverted to a hocus-pocus attitude (stemming directly from alchemic tradition) once common but happily now increasingly rare among photographic promotion schemes.

Stephen Timoshenko. 60th Anniversary Volume. Pp. 277+viii, Figs. 144, 16×24 cm. The Macmillan Company, New York, 1938. Price $5.00.

This book represents a practice which is not common in this country—that of honoring a man who is an acknowledged leader in his field, by dedicating to him a group of papers by those who have been associated with him. The list of authors presents an impressive array of names of men recognized as authorities in the field of the mechanics of solids. Several of the authors are Europeans whose works are well known in this country. Four of the papers are printed in German, the remaining twenty-four being in English.

The papers are quite varied in the nature of the subject matter treated and also in the degree of complexity of the mathematics employed. The subjects discussed by the

various authors deal with or involve the following phases of the field of solid mechanics:

Theory of Elasticity	Fatigue and Tensile Testing
Related Mathematics	Treatment and Analyses of Test Data
Photoelasticity	Plastic Deformation, including Recrystallization, Creep and Relaxation
Buckling	
Vibration	
Friction	

In general, the papers have been carefully prepared and reflect the authors' extensive knowledge of the subjects. Many of the papers contribute new material to the field of solid mechanics while others provide summaries of the present status of various branches of this field.

The book is primarily a testimonial to Dr. Timoshenko—one which, as anyone who has worked in the field of mechanics in the past generation must agree, he richly deserves. The book was obviously not intended as a text-book and is not well suited for this purpose. The papers have not been presented specifically for the purpose of assisting the designing engineer and consequently such a person will probably find the book of little direct use. The book should have its greatest appeal among those whose primary interest lies in the field of solid mechanics. It should be of particular value to men engaged in research, either directly in the field of mechanics or in other fields which employ applied mechanics as a tool.

Few readers will be vitally interested in all of the papers but each should find something of particular value in the branch or branches of the field of mechanics in which he is particularly interested and, at the same time, obtain a general idea of the present status of knowledge in other branches.

R. L. TEMPLIN
Aluminum Company of America
Prepared with the assistance of members of my staff

Here and There

Dr. James S. Allen, University of Minnesota, has been appointed to an associate professorship in the Department of Physics, Kansas State College, Manhattan, Kansas.

★

The University of Maine announces that Professor Clarence E. Bennett has been appointed Head of the Department of Physics.

★

Professor W. R. Fredrickson has been appointed Chairman of the Physics Department, Syracuse University. R. A. Porter, Chairman for twenty years, will continue as a full-time member of the staff. R. F. Humphreys, Ph.D., Yale, '39, has been added to the staff as an instructor.

From the Physics Department of the University of Illinois come the following announcements: Associate Professor P. Gerald Kruger has been promoted to the rank of full professor, Assistant Professors G. M. Almy and H. M. Mott-Smith to the rank of Associate Professor, and Dr. L. J. Haworth to the rank of Assistant Professor from that of Associate.

★

At the University of Wisconsin, Dr. R. G. Herb has been promoted to Associate Professor of Physics.

★

Dr. S. L. Gerhard, formerly in the Explosives Division of the Bureau of Mines in Pittsburgh, has recently gone to the United States Rubber Company as a staff member of the Development Department of the Tire Cord Division, situated at Hogansville, Georgia.

★

Among those receiving honorary doctorate degrees at Harvard University were Dr. Percy W. Bridgman, Hollis Professor of Mathematics and Natural Philosophy, Harvard University, and Dr. Charles F. Kettering, Engineer, President of the General Motors Research Corporation, Dayton, Ohio.

★

Dr. Edward J. Moore, Professor of Physics at the University of Buffalo, has been appointed Dean of the Graduate School of Arts and Science.

★

Morris E. Leeds, founder and President of the Leeds and Northrup Company, is assuming the position of Chairman of the Board of Directors, and Charles S. Redding, Vice President in Charge of Research and Engineering, becomes President, in an expansion of the Company's executive set-up effective July 10.

★

Calendar of Meetings

September	
4–12	International Congress of Mathematicians, Cambridge, Mass.
4–15	International Union of Geodesy and Geophysics, Washington, D. C.
11–15	American Chemical Society, Boston, Mass.
20–23	Institute of Radio Engineers, New York, N. Y.
October	
5–7	American Institute of Mining and Metallurgical Engineers, Coal Division, Columbus, Ohio.
12–14	Optical Society of America, Lake Placid, N. Y.
13–14	Society of Rheology, National Bureau of Standards, Washington, D. C.
23–25	American Institute of Mining and Metallurgical Engineers, Metals Division, Chicago, Ill.
23–27	American Society for Metals, Chicago, Ill.
November	
2	U. S. Institute for Textile Research, New York, N. Y.
2–4	American Institute of Physics, Symposium on Temperature: Its Measurement and Control in Science and Industry, New York, N. Y.
3–4	Acoustical Society of America, Iowa City, Iowa.
2–4	American Institute of Mining and Metallurgical Engineers, Industrial Minerals Division, Tuscaloosa, Ala.
15–17	American Institute of Chemical Engineers, Providence, R. I.
December	
1–2	American Physical Society, Chicago, Ill.
27–Jan. 2	American Association for the Advancement of Science, Columbus, Ohio.
28–30	American Physical Society, Columbus, Ohio.
28–30	Geological Society of America, Minneapolis, Minn.

Contributed Original Research

Bactericidal Effects of Ultraviolet Radiation Produced by Low Pressure Mercury Vapor Lamps

L. R. KOLLER
Research Laboratory, General Electric Company, Schenectady, New York
(Received March 1, 1939)

The killing effect of 2537A radiation has been studied, both for bacteria suspended in air and bacteria and molds on surfaces. A 15-watt sterilizing lamp (giving 25 μw/cm of 2537A radiation at 1 meter from the lamp) will kill 97–99 percent of B. Coli suspended in air at a distance of 24 inches in 10 seconds. Accordingly in an air duct a 15-watt lamp can sterilize approximately 200 cu. ft. of air per minute. A 15-watt sterilizing lamp will kill B. Coli on the surface of agar at a distance of 10″ in 20 seconds. The Bunsen Roscoe reciprocity law applies to the killing of bacteria by ultraviolet radiation between the intensities of 2000 μw/cm^2 and 1.3 μw/cm^2. The lethal dose of 2537A radiation for B. Coli on agar is 6600 μw sec./cm^2. For practical purposes the effect of temperature may be neglected. A film of grease is very effective in shielding bacteria from radiation. The lethal dose of 2537A radiation for black mold spores is about 45 times that for B. Coli. The reciprocity law applies. The sensitivity of mold spores decreases with increasing wave-length and is negligible for 3650A. Low pressure lamps in ultraviolet transmitting glass produce concentrations of ozone of the order of 0.1 part per million. From these experiments it may be concluded that low pressure mercury vapor lamps when used under the proper conditions are very powerful bactericidal agents if the bacteria are directly exposed to the radiation, but that the effectiveness is greatly reduced by even such slight shielding as is offered by a film of grease.

THE bactericidal action of ultraviolet radiation has been known for at least 62 years. In 1877 Downes and Blunt[1] demonstrated that sunlight killed bacteria and showed that the action was associated chiefly with the short wave-length component of the radiation. Since then this field has been steadily explored. The first work was largely qualitative, but as early as 1905 Hertel[2] made studies in which he measured the incident energy by means of a thermopile. More recent work by Coblentz and Fulton,[3] Gates,[4] Wyckoff,[5] Hollaender and Claus[6] and others has yielded much quantitative information of a fundamental nature. Comprehensive historical summaries and good bibliographies have been given by Duggar[7] and by Laurens.[8]

Interest in this field has been intensified with the recent development of low pressure mercury vapor lamps in envelopes of high transmission glass which make it possible to obtain large amounts of the ultraviolet energy at low cost. Some of the characteristics of such lamps have been given by Hibben and Blackburn.[9]

Most of the following work was done with B. Coli Communis. Some measurements were also made with B. Prodigiosus and B. Subtilis. The bacteria were grown on a nutrient agar very kindly supplied by the Pathology Laboratory of the Ellis Hospital. The experiments on molds were carried out with the cooperation of Dr. P. Zahl of Union College on a strain of aspergillus niger supplied by the Haskins Bio-Physics Laboratory of Union College.

Several different types of lamps were used during the course of the work. All of these were of the low pressure mercury vapor type designed to give a high output of radiation of wave-length 2537A.* Most of the work was done with a 15-watt

[1] Downes and Blunt, Proc. Roy. Soc. **26**, 488 (1877).
[2] Hertel, Zeits. Allgem. Physiol. **5**, 95 (1905).
[3] W. W. Coblentz and H. R. Fulton, Sci. Papers Nat. Bur. Stand. **19**, 641 (1924).
[4] F. L. Gates, J. Gen. Phys. **13**, 231, 249 (1929); **14**, 31 (1930).
[5] R. G. Wyckoff, J. Gen. Phys. **15**, 351 (1931).
[6] A. Hollaender and B. M. Duggar, J. Bacteriology **36**, 17 (1938).
[7] B. M. Duggar, *Biological Effects of Radiation*, Vol. II (McGraw Hill Book Co., 1936).
[8] H. Laurens, *The Physiological Effects of Radiant Energy* (Chem. Catalog Co., 1933).
[9] S. G. Hibben and P. W. Blackburn, El. Eng. **57**, 455 (1938).

* This radiation is very harmful to the eyes. They should always be adequately protected when working with these lamps. Direct exposure of the skin to the radiation should also be avoided as much as is practicable.

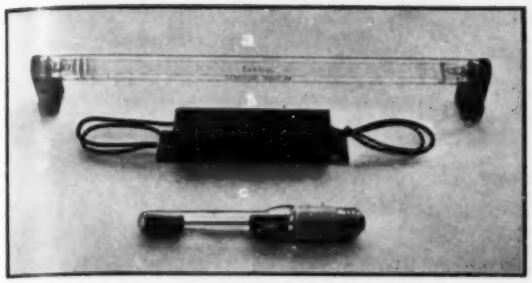

FIG. 1. (a) 15-watt sterilizing lamp. (b) reactor for 15-watt lamp. (c) 5-watt sterilizing lamp.

T8 sterilizing lamp of the form shown in Fig. 1. This is a hot cathode lamp in a tube one inch in diameter and 18 inches long. It requires a small reactor also shown in the figure. The lamp operates at a current of 0.25 amp. with a voltage drop of 60 volts. About 95 percent of the energy radiated is in the 2537A line. Since (as will be shown later) the longer wave-lengths have very little bactericidal effect the lamp is effectively a monochromatic source of 2537A radiation. The intensity of 2537A radiation at a distance of one meter from the lamp is approximately 15 microwatts per sq. cm. The energy distribution in the ultraviolet spectrum is shown in Table I. A few measurements were made with a 5-watt T10 sterilizing lamp which is also shown in Fig. 1. The spectral energy distribution of the radiation from this lamp is similar to that for the T8. The intensity of the 2537A line at a distance of 1 meter from the lamp is 1 microwatt per sq. m.

In order to study the bactericidal action of ultraviolet radiation it is essential to have some measure of the killing or of the inactivation of the bacteria. For the purposes of this investigation the ability to form colonies was the most convenient criterion. If the organisms when placed on the surface of nutrient agar and incubated for 18 to 24 hours at 37.5°C did not form colonies they were said to have been killed.

It has been shown by many investigators that the survival ratio of bacteria when subjected to some lethal agent is an exponential function of time of the form

$$N = N_0 E^{-KIt} \qquad (1)$$

where N = the number of organisms surviving at any time t, N_0 = the number of organisms at $t=0$, K = a constant depending upon the susceptibility of the organisms to the radiation and I = radiation intensity.

This is similar to the expression for the rate of a monomolecular chemical reaction with KI taking the place of the reaction rate. For precise work it is desirable to make counts of the number of colonies surviving after various periods of irradiation and from these counts to determine K. For the practical purposes of this investigation, however, it was sufficient to determine the quantity of radiation which would insure that no bacteria survived (according to the above criterion of survival).

KILLING IN AIR

The killing of bacteria suspended in air is the simplest case to study since here we have the organism free from any surrounding medium except, of course, the surrounding air. Studies of the killing in air have been made by Whisler,[10] Wells,[11] Rentschler,[12] Hart[13] and others.

TABLE I. *Spectral intensity perpendicular to axis of arc for 15-watt low pressure mercury vapor bactericidal lamp.*

LINE	WAVE-LENGTH BAND	MILLIWATTS PER STERADIAN	MICROWATTS PER SQ. CM 1 METER FROM LAMP
2483	2470–2497	0.1	0.01
	2497–2524	0.6	0.06
2537	2524–2550	160.0	16.0
	2550–2607	0.3	0.03
2652	2607–2724	0.2	0.02
2804	2724–2820	0.1	0.01
	2820–2861	0.1	0.01
2894	2861–2926	0.1	0.01
2967	2926–2998	0.6	0.06
3022	2998–3050	0.3	0.03
3129	3050–3226	2.9	0.29
3341	3226–3434	0.2	0.02
	3434–3601	.05	0.005
3654	3601–3696	3.1	0.31
	3696–3798	0.3	0.03
	3798–3909	0.5	0.05

[10] B. Whisler, Harvard Univ. Thesis, May, 1936.
[11] W. F. Wells, J. Am. Med. Assn. **107**, 1698, 1805 (1936); Am. J. Public Health **28**, 343 (1938); J. Frank. Inst. (1939).
[12] H. C. Rentschler, Am. Soc. Refrig. Eng. Summer Meeting, 1938.
[13] D. Hart, Arch. Surgery **34**, 874 (1937); **37**, 521 (1938); J. Thoracic Surgery **6**, 45 (1936).

The experimental arrangement used is shown in Fig. 2. The bacteria are sprayed into the two-liter mixing bottle *B* and then drawn into the galvanized metal tank *T*. In this tank after passing through four layers of 60 mesh copper gauze to decrease turbulence, the air passes under a window of 0.001-inch Cellophane through which it is irradiated. (The nonmoisture proofed Cellophane used for this purpose has a transmission of 75 percent for the 2537A line.) The lamp, in a reflector, can be placed at various heights

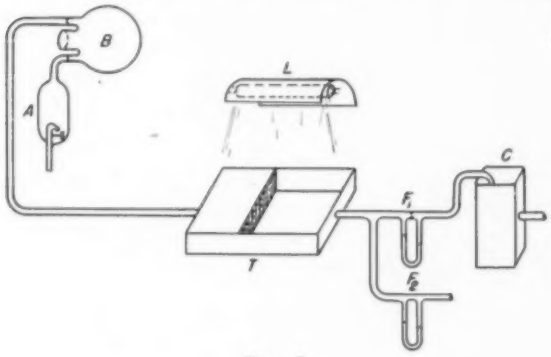

FIG. 2.

above the tank. A part of the air then passes into a Wells[14] centrifuge *C*. By means of the flow gauges *F*1, *F*2, the rate of flow through the tank and the centrifuge is measured. This is controlled by pinch cocks on the rubber hose connections. Suspensions were made from one-day old cultures of B. Coli Communis. One loop full of bacteria was suspended in 100 cc of distilled water. This suspension was sprayed into the mixing bulb by means of a Parke Davis adrenalin atomizer. The atomizer was refilled for each centrifuge tube. It was operated by means of compressed air, the pressure of which was regulated by a reducing valve. Control experiments showed that the death rate of the bacteria in the distilled water in the half-hour or so required for an experiment was not significant. No especial precautions were taken to prevent clumping and throughout this work a colony may be due to a clump as well as single organism. The concentration in one typical suspension was 10^4 organisms per cc. The time of exposure was varied by varying the rate of air flow and by covering up portions of the tank window so that the air was only exposed during a part of its passage through the tank. The centrifuge samples consisted of 2.5 cu. ft. taken at the rate of 0.5 cu. ft. per minute.

In Fig. 3 is shown a typical set of centrifuge tubes. By means of counts of colonies at three different zones in each tube the number of colonies per sq. cm. was determined.

It has been noted by Wells[11] and Whisler[10] that the lethal effect of the radiation depends upon the relative humidity of the atmosphere. The amount of moisture introduced by the atomizer is too small to affect the humidity appreciably. In order to obtain high humidities air was drawn into the mixing bulb from a small portable type of room humidifier. In this way humidities as high as 96 percent (measured in the tank) were obtained.

Some typical results are shown in Table II, where each value represents the count on a single tube. Although there is considerable spread in the measurements, probably due to experimental errors such as clumping, unevenness in atomizer operation and centrifuge speed, it is evident that at humidities below 80 percent killing is 97 to 100 percent complete in ten seconds with a maximum distance of 24 inches of any portion of the air stream from the lamp. The initial number of colonies in these experiments ranged from 700 to 7000 per cu. ft. At humidities above 80 percent the radiation is considerably less effective as can be seen from the last three values in the table.

FIG. 3. Centrifuge "tubes exposed at 24" from 15-watt sterilizing lamp. No. 43, control. No. 44, 10-sec. exposure. No. 45, 5-sec. exposure. No. 46, 1-sec. exposure.

[14] W. F. Wells, Year Book 1936–37 Supplement to Am. J. Public Health **27**, 3 (1937); Am. J. Public Health **28**, 343 (1938).

TABLE II. *Killing of B. Coli suspended in air at 24" from 15-watt sterilizing lamp. The initial number of colonies in these experiments ranged from 700 to 7000 per cubic feet.*

Relative Humidity	Percent Reduction in Number of Colonies		
	10-sec. Exposure	5-sec. Exposure	1-sec. Exposure
28	98	—	72
36	100	99	87
47	99+	—	—
50	99+	—	69
53	98	—	—
56	99+	87	—
61	99+	94	90
62	100	—	—
76	97	93	—
96	82	44	57
86	50	—	—
92	60	—	—

If humidities below 60 percent are arbitrarily defined as low and 80 to 100 percent as high, calculation of the constant K in Eq. (1) shows that for low humidities the radiation is at least five times as effective as for high humidities. This factor must be considered in any application where high humidities are apt to be encountered. This effect of humidity is not due to the absorption of 2537A radiation by water in the air or in a film surrounding the organism. A thickness of two cm of pure water has a transmission of about 96 percent for this wave-length. It seems more reasonable to think that the effect is a physiological one.

From the values obtained at low humidities which indicate 98 to 100 percent sterilization in 10 seconds it is possible to calculate the quantity of air which could be sterilized by a single lamp in a duct. Let us assume a 15-watt lamp parallel to the axis of a duct having a two-foot radius. Neglecting end effects and assuming uniform radial radiation and stream line air flow, a particle in the air will be subject to uniform radiation intensity while it is traveling a distance equal to the length of the lamp, that is 18". For complete sterilization it must not traverse this path in less than ten seconds. Accordingly the volume of air which can be treated by a single lamp thus placed is $\pi r^2 \times 1.5/10 = 1.88$ cu. ft./sec. or 113 cu. ft./min. Assuming the reciprocity law and correcting for the transmission of the Cellophane window this value would be increased to 150 cu. ft./min. This is in good agreement with a value of 97 to 99 percent killing with a single lamp in a one-ft. sq. duct for a flow of 200 cu. ft./min. obtained by Dr. Robertson at the Hospital for Sick Children, Toronto.

The quantity of air which can be treated by a single lamp is a constant independent of the dimensions of the duct. This can be seen from very simple considerations. If we consider the air at the edge of a given duct where the intensity is only just sufficient to sterilize in the time required to pass the lamp and then assume the duct expanded to twice its radius, the intensity at the edge would be reduced to $\frac{1}{4}$, according to the inverse square law. At the same time, however, since the duct cross section is also increased fourfold the air velocity (for the same volume of air) is decreased to $\frac{1}{4}$ of its previous value and the product of intensity and time remains constant.

By making the walls of the duct of aluminum or other material having a high coefficient of reflection for ultraviolet radiation, the volume of air treated per lamp might be somewhat increased. In practice, however, this would involve the problem of keeping the surface free from dust and films which would impair its reflectivity.

The most obvious application of the sterilization of air is in the ducts of ventilating and air conditioning systems where it is desired to sterilize the air brought to a room.[15] The benefits to health due to such procedure remain to be determined but it is a fact that it is possible by simple means to insure a supply of practically sterile air. Ultraviolet radiation has also been used to sterilize the air in hospital operating rooms[13, 16] and in the form of barriers to prevent cross-infection in children's hospitals[16–18] as well as in school rooms and other institutions. Aside from the application to ordinary ventilating there are possible industrial applications, such as in the preparation of serums, and in industries where it is necessary to handle and pack materials in a sterile atmosphere.

The effect of dust has not yet been studied. It seems probable that in a very dusty atmosphere some of the bacteria might be attached to dust particles and thus shielded from the radiation.

[15] F. W. Robinson, J. Ind. Eng. Chem. **31**, 23 (1939).
[16] W. F. Wells, Modern Hospital **51**, 1 (1938).
[17] C. F. McKhann, Am. J. Diseases of Children **55**, 1 (1938).
[18] Robertson *et al.*, Am. J. Diseases of Children, in course of publication.

Killing on Surfaces

Killing of bacteria on surfaces has been studied by many investigators. Particularly good measurements have been made by Coblentz[3] and Fulton, Gates,[4] Wyckoff[5] and in liquids by Hollaender and Claus.[6]

In the present work Petri dishes were sterilized and filled with agar in the usual manner. A suspension of the bacteria was then sprayed onto the surface of the plates with a DeVilbiss atomizer. One squeeze of the bulb with the nozzle of the atomizer at 18″ to 24″ from the plate gave a satisfactory droplet distribution. The plates were then exposed under different conditions, incubated overnight and compared with controls.

The exposure times for complete killing of B. Coli at 10 inches from several different kinds of ultraviolet sources are given in Table III.

A typical set of plates is shown in Fig. 4.

Reciprocity Law

The reciprocity law was tested in the following manner. Five plates were sprayed with B. Coli. One plate was kept as a control, the other four were exposed at various distances from the lamp between one and ten and one-half inches, corresponding to a ninefold range in ultraviolet intensity. The first plate was exposed at a distance of one inch, half of the plate being exposed for two seconds and the other half for four seconds. The other plates were exposed at $3\frac{1}{4}''$, $5\frac{3}{4}''$, $10\frac{1}{2}''$, in each case the time being increased to exactly compensate for the decreased intensity (as measured by a photo-tube) so that the product of intensity times time was kept constant. The plates are shown in Fig. 5. It can be seen that at one inch the two-second exposure was not quite long enough to give complete killing while for the four-second exposure all bacteria were killed. Thus at this distance the time for complete killing may be taken as approximately three seconds.

Table III.

Lamp	Time
15-watt T8 sterilizing (in high transmission glass)	20 seconds
5-watt T10 positive column sterilizing (in high transmission glass)	12 minutes
300-watt Uviarc (quartz)	10 seconds

Similarly for the plate which was exposed at $10\frac{1}{4}$ (or $\frac{1}{9}$ of the intensity of the first one) the time for complete killing lay between 16 and 32 seconds, let us say 24 seconds. Thus for a ninefold decrease in intensity the same killing effect was obtained for an approximately eightfold increase in exposure time. Within the limits of the experiment therefore, the Bunsen Roscoe reciprocity law may be said to apply. In the same way the relation was extended to lower intensities and found to be valid over a range of intensities from 2200 $\mu w/cm^2$ to 1.3 $\mu w/cm^2$. Over this range the quantity of 2537A radiation required for complete killing of B. Coli sprayed onto the surface of nutrient agar is 6600 μw sec./cm^2. These measurements of the reciprocity relation made at room temperature are difficult to interpret. At the long exposure times the bacteria reproduce during the course of the experiment so that it is not necessarily a single individual that is being

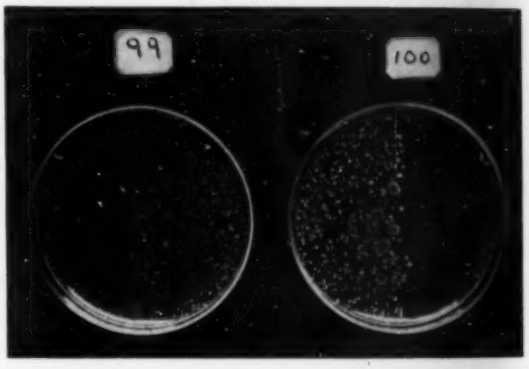

Fig. 4. Plates exposed 10″ from 5-watt sterilizing lamp. No. 99, left half control, right half 4-minute exposure. No. 100, left half 8-minute exposure, right half 16-minute exposure.

studied. In order to confine the observations to a single individual, a slightly different procedure was adopted. The plates were placed in a refrigerator at approximately 0°. At this temperature no growth takes place. The plates were irradiated through a Cellophane window in the top of the refrigerator and then incubated in the usual manner. Under these conditions the reciprocity relation was tested and found to hold over the range studied. This was from intensities of 40 $\mu w/cm^2$ to 0.11 $\mu w/cm^2$ corresponding to exposure times from three minutes to 18 hours.

In all probability there is a threshold value

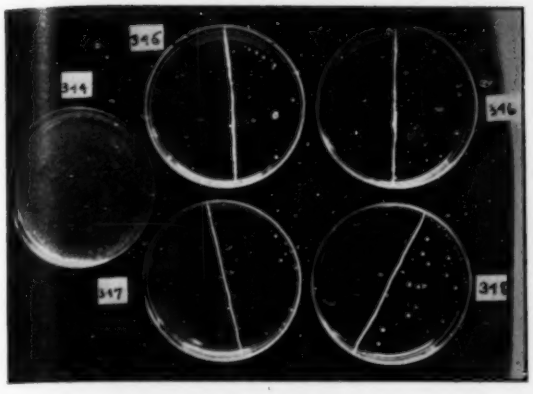

FIG. 5. Test of reciprocity law. B. Coli exposed to same total energy at various intensities. No. 344, control. No. 345, right 2 seconds exposure, left 4 seconds exposure. No. 346, right 4 seconds exposure, left 8 seconds exposure. No. 347, right 8 seconds exposure, left 16 seconds exposure. No. 348, right 16 seconds exposure, left 32 seconds exposure.

at still lower radiation intensities. This point is under investigation at present. Sublethal effects have been described by Hollaender and Duggar.[19]

The radiation did not have any effect on the nutrient medium. This was tested by exposing plates to the radiation before spraying on the bacteria. Over the range of exposures used there was no noticeable difference in the development of bacteria on plates which had been exposed before spraying and those which had not.

A few measurements were also made on other organisms: B. Prodigiosus required about the same dosage for complete killing as B. Coli: A 24-hour old culture of B. Subtilis required an exposure of three minutes at 10″ from a 15-watt lamp for complete killing or 60,000 μw sec./cm^2, approximately nine times as much as the B. Coli. This organism is a spore former and it seems reasonable to suppose that a difference of this order of magnitude is to be found between other nonspore formers and spore forming organisms. No conclusions can be drawn from the above data as to the effect of radiation on other forms of bacteria or viruses. The effect of the age of the culture was not studied. Rather inconsistent results on the effect of the age of a culture on its susceptibility have been reported by various experimenters.[7, 20]

It has been shown by a number of investigators that the maximum killing effect for bacteria is observed with radiation of wave-length about 2650A. The maximum is a rather broad one and since the low pressure Hg lamp emits such a large proportion of its radiant energy at 2537A it is well suited for bactericidal work, in spite of the fact that this is not the most effective wave-length for all organisms. At longer wave-lengths than 2650A the killing power falls off to a marked degree. Hollaender and Claus[6] have shown that 2950A is about $\frac{1}{6}$ as effective as 2537A for killing B. Coli. Wyckoff sets the ratio at $\frac{2}{3}$ while according to Gates it is $\frac{1}{11}$.

No significant difference in degree of killing was found between B. Coli irradiated at 37½°C and those irradiated at 11°C. According to Gates[4] there is a slight temperature coefficient, approximately 10 percent more energy being required for the same degree of killing for a 10°C rise in temperature between 5 and 35°C. This difference would not have been noticeable in the present experiments.

No attempt was made to study the effect of humidity since the bacteria were on the surface of a moist medium. The dose for killing on the agar was comparable with that for killing in humid air.

It must be emphasized that these data apply only to bacteria in relatively thin films on the surface of a medium. The absorption of 2537A is so high that enormously greater intensities are required for bacteria even at very slight depths below the surface. Of course organisms in cracks or folds of opaque media cannot be reached at all.

Some experiments were undertaken to study the possibility of sterilizing dishes and glassware by means of radiation. Petrie dishes were soiled in various ways with greasy films containing bacteria. The surfaces were irradiated and cultures from the soiled surface were then made by the usual methods.[21] These were studied for the survival of the bacteria. Results varied greatly depending upon the nature of the film on the glassware. In some cases the glasses could be effectively sterilized by a 5-second exposure at 5″

[19] A. Hollaender and B. M. Duggar, J. Bacteriology **36**, 17 (1938).

[20] Ad Liechti and E. Feistman, Strahlentherapie **62**, 26 (1938).

[21] Calver, *Techniques for the Bacteriological Examination of Drinking Glasses*. Mimeograph Public Health Comm. of the Cup and Container Inst., 30 Rockefeller Plaza, New York City.

TABLE IV.

Run No.	Enclosure	Type of Lamp	Ozone conc. in Pts./million	Remarks
1	Box 1 cu. ft.*	15-w	0.89	Sampling intake 1″ fom lamp
2	Box 1 cu. ft.*	15-w	0.57	Sampling intake 7″ from lamp
3	Box 1 cu. ft.*	5-w	0.62	Sampling intake 1″ from lamp
4	Box 1 cu. ft.*	5-w	0.58	Sampling intake 7″ from lamp
5	Room 500 cu. ft.*	15-w	0.16	Sampling intake 5′6″ from lamp and near wall
6	Room 500 cu. ft.*	15-w	0.064	Sampling intake 5′ from lamp
7	Room 500 cu. ft.*	15-w	0.187	Sampling intake 5′ from lamp 6″—fan directed at lamp
8	Room 500 cu. ft.*	15-w	0.075	Room ventilated 8 displacements per hour
9	Refrigerator 2 cu. ft.	5-w	0.12	$t=29°C$
10	Refrigerator 2 cu. ft.	5-w	0.044	$t=11°C$
11	Refrigerator 2 cu. ft.	5-w	0.075	$t=8.5°C$
12	Refrigerator 2 cu. ft.	5-w	0.03	$t=2°C$

* Painted with Glyptal paint.

from a 15-watt lamp. In other cases bacteria survived an exposure of several minutes, due to the absorption of the radiation in the film. It was concluded that while sterilization of glassware was possible by means of radiation it was very important to have fairly clean surfaces to begin with.

Molds

Experiments were carried out on the lethal effect of radiation on the spores of the black mold Aspergillus Niger. These will be reported separately in a paper by Zahl and Koller. It was found that the mold spores required about 45 times as much radiation for complete killing as the bacteria. The reciprocity law was found to hold within the range of intensities studied (71 to 1175 $\mu w/cm^2$). No appreciable humidity effects could be detected. As in the case of the bacteria the killing action of the radiation fell off with increasing wave-length. More than 50 times as much energy of wave-length 3129A was required to give thirty-eight percent killing as of 2537A, while an exposure of 8 hours to three times this intensity of 3650A, did not produce any appreciable effect.

Ozone Production

Some measurements of ozone production by low pressure lamps were made. The procedure consisted in placing the lamp in a suitable enclosure, drawing off air from this enclosure and bubbling it through KI solution. The free iodine was determined by titration and from this the amount of ozone in parts per million by weight was calculated.

The sample of air withdrawn for analysis was of the order of 10 cu. ft. and was taken at the rate of about 1 cu. ft./hr. or less so that even in the case of the smallest enclosure used (1 cu. ft.) the concentration is practically the equilibrium value. The results are shown in Table IV. The room temperature was approximately 25°C and the relative humidity 30 percent.

From the table it can be seen that the lamps produce concentrations of ozone of the order of tenths of a part per million.

The result of runs Nos. 1 and 2 as compared with Nos. 3 and 4 is rather surprising, showing an ozone yield of the same order of magnitude for the 15-w and 5-w lamp although there is a great difference in the relative outputs of 2537A radiation.*

In the 500 cu.ft. room the odor of ozone while not strong was distinctly recognizable in all four experiments.

The decrease in ozone concentration with decreasing temperature shown in runs 9–12 is probably due to the decrease in output of the lamp at low temperatures.

Experiments are in progress on the effects of these low concentrations of ozone on bacteria and molds.

Preliminary experiments indicate that the killing effect of these low concentrations of ozone is small compared with the effects produced by the direct radiation from the lamps.

* Recent studies show large differences in ozone yield between different lamps of the same type.

Energy Measurements of Reigniting A.C. Arcs

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(Received March 16, 1939)

An oscillographic study of arcs formed between silver contacts in the rupturing of 120-volt a.c. circuits containing resistive loads shows that reignition of the arc occurs at low speeds of contact separation. Data have been obtained by means of a ballistic wattmeter showing the effect of current and line voltage on arc energy for silver contacts opening at speeds from 0.024 to 16.7 inches per second. In the low speed range reignition is more prevalent at 225 volts than at 115 volts, and restriking of the arc occurs at higher speeds for higher currents. The formation of an arc in reigniting cycles is believed to be due to field emission of electrons, an average field of 0.30×10^6 volts/cm being found for all cases of reignition observed. Reignition occurred at potentials as low as 72 volts and the intermediate glow discharge normally observed in the interruption of inductive circuits did not appear.

Introduction

THE life of contacts in various circuit breaking devices depends upon the amount of energy dissipated in the arc when the circuit is being opened. A reduction in the energy of arcs in such devices decreases the quantity of material lost from the contacts and results in a more satisfactory performance and a longer useful life. While generally reignition may not take place in most circuit breaking devices commonly used in low voltage a.c. service, it does occur in some cases and is a contributing factor to the arc energy. A full understanding of the conditions which lead to restriking of the arc between switch contacts should lead to improvement in the performance of existing circuit breaking devices and to a simplification of the design of new devices for use on a.c. circuits.

It is well known that satisfactory interruption of low voltage, low current a.c. circuits can be obtained with relatively low contact opening speeds. To determine more definitely the effect of contact speed, an investigation was conducted in which arc energy was measured with a ballistic wattmeter.[1] Measurements in a 35-amp. circuit showed that a decrease in arc energy took place as the speed of contact separation was reduced from 16.7 to 1.5 inches per second. Upon further lowering of the contact opening speed from 1.5 to 0.2 inch per second, however, the arc energy increased at a rapid rate.

The decrease in arc energy with the reduction in contact opening speed was shown to result from lowering of the average arc voltage due to the smaller electrode spacing which exists during the period of arcing. On the other hand, the increase in arc energy as the contact speed was reduced below 1.5 inches per second, was attributed to reignition of the arc. But, according to the available information on reignition, which will be briefly reviewed in the next section, restriking should not occur while rupturing a 115-volt noninductive a.c. circuit, since a "dielectric strength" of the order of 200 volts is established practically instantaneously in the gap space. However, no work on reignition has been done with gaps of the order of 0.0002 in. such as those investigated in the present work. Furthermore, most investigations of reignition have been done with low power factor circuits, while circuits with nearly unity power factor have not been studied.

The arcing which takes place when circuits consisting of noninductive heater elements are opened was further investigated by extending previous measurements of arc energy on 35 amperes to a lower contact speed and obtaining additional data on 25 and 15 amperes at both 115 and 225 volts, 60-cycle a.c. Tests were also made using an oscillograph equipped with a watt-element. Contact opening speeds from 0.024 to 16.7 inches per second were used, this range covering speeds most commonly found in circuit breaking devices for a.c. service. In the entire

* In charge of research laboratory, Robertshaw Thermostat Company, Youngwood, Pennsylvania.
[1] S. G. Eskin, "Effect of Contact Opening Speed on Arc Energy in A.C. Switching," Gen. Elec. Rev. **42**, 81–86 (1939).

investigation the contacts were fine silver, since silver is the most commonly used material for small arcing contacts.

Review of Previous Investigations of Reignition

The reignition of a.c. arcs has been studied by a number of investigators during the past decade and considerable information is available. In general, the procedure employed consisted of setting up an arc between a pair of stationary electrodes with a fixed gap and measuring by various methods the "dielectric strength" of the gap space expressed in terms of potential required to reignite the arc. These researches were done with electrodes of different materials and with gaps varying from $\frac{1}{32}$ inch to $\frac{3}{4}$ inch. To obtain a stable arc with metal electrodes, usually large currents and high voltages or high inductances were necessary.

The general conclusion reached is that the gap space almost instantly recovers a "dielectric strength" of considerable magnitude, further recovery proceeding at a much slower rate.[2] The values for the initially-recovered "dielectric strength" for copper and aluminum are 160 volts and for brass 230 volts, depending for a given material solely on the gas medium.[3] It has been found that this ability to withstand breakdown builds up at a faster rate with a gap of $\frac{1}{16}$ inch than with a $\frac{1}{8}$-inch gap.[4] The restriking potential depends on the material of the electrodes, having a value of 360 volts for a $\frac{1}{16}''$ copper arc carrying a current of 92 amperes at 920 volts.[5] The restriking potential for silver has not been determined. The thermal conductivity of the electrode material is a very important factor, the reignition potential being higher for materials of high thermal conductivity.[6]

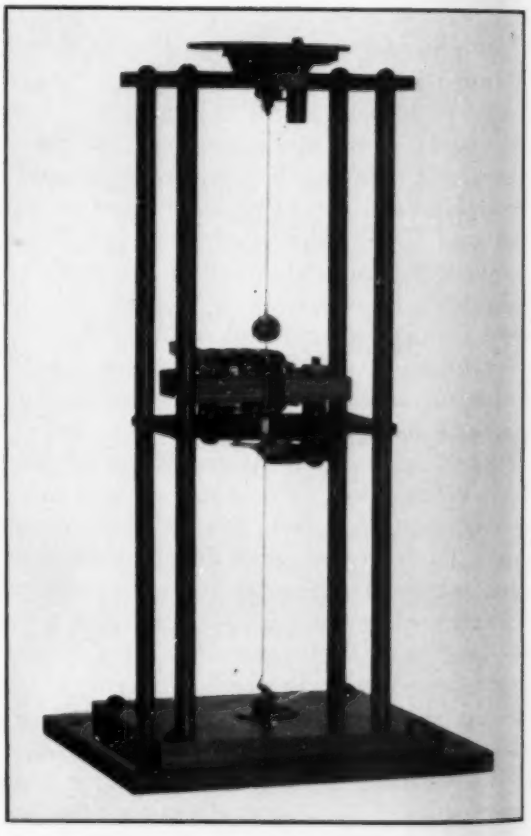

Fig. 1. General Electric ballistic wattmeter and suspended armature light beam wattmeter element. Two ranges are provided: 0 to 10 and 0 to 20 watt-seconds, and the rating is 40 amperes, 220 volts.

[2] J. Slepian, "Extinction of an A.C. Arc," Trans. A. I. E. E. **47**, 1398–1407 (1928).
[3] T. E. Browne, Jr., "Extinction of Short A.C. Arcs," Trans. A. I. E. E. **50**, 1461–1464 (1931).
[4] T. E. Browne, Jr. and F. C. Todd, "Extinction of Short A.C. Arcs Between Brass Electrodes," Phys. Rev. **36**, 726–731 (1930).
[5] F. C. Todd and T. E. Browne, Jr., "Restriking of Short A.C. Arcs," Phys. Rev. **36**, 732–737 (1930).
[6] S. S. Mackeown, J. D. Cobine and F. W. Bowden, "Reignition of an Arc at Low Pressures," Elec. Eng. **53**, 1081–1085 (1934).

Apparatus and Method

The study of arcing on a.c. by means of energy measurements with a ballistic wattmeter makes it possible to evaluate the effect of various factors involved directly in terms of energy units. A detailed description of the apparatus and method employed in the present investigation is given in a recent paper by the author.[1] Fig. 1 shows a general view of the measuring instrument, especially designed by the General Electric Company for this study, and its armature element. The construction of this wattmeter and the method of its operation and calibration have been described in detail elsewhere.[7] The readings of the ballistic wattmeter give energy values according to the expression

$$W_a = \int i v_a dt \qquad (1)$$

over the period of duration of the arc, where W_a = arc energy in watt-seconds, i = current in amperes, and v_a = arc voltage. The instrument is calibrated to read directly in watt-seconds. Being of the light beam type, a large number of readings can be obtained with it in a relatively short time.

To obtain contact opening speeds over a wide range, a special device was built by means of which two contacts could be separated with a variety of uniform linear speeds ranging from 0.024 to 16.7 inches per second, giving a maximum speed ratio of 1 to 700.[1] Additional equipment consisted of an electromagnetic oscillograph for measuring the interrupted current, line voltage, arc voltage, and arc power. The oscillograph contained a watt-element for arc power measurements.

Effect of Current

The effect of current was studied by making arc energy measurements at 15, 25 and 35 amperes, 115 volts. The results of these measurements are shown in Fig. 2. Each point on the curves of this figure represents the average of 300 individual readings. Since contact separation on a. c. may start at any place on the current wave, it was necessary to take a large number of readings, so that statistical variations could be eliminated as much as possible in determining the effect of speed on the average arc energy.

The average arc energy curves of Fig. 2 have two distinct sections. The sections to the right of the dotted critical contact speed curve show that as the contact speed is reduced the average arc energy decreases. This is due to the fact that at slower speeds the gap at the instant of zero current is smaller, resulting in a lower arc voltage and therefore a lower arc energy. The longest arcing time with contact speeds above the critical value is equal to the period of the half-cycle of the 60-cycle current, since at these speeds no reignition takes place. On the other hand, the sections to the left of the dotted curve show that further reduction of contact speed results in an increase of arc energy. Since no increase in arc voltage is possible with this reduction in speed the increase in arc energy below the critical speed is attributed to reigniting of the arc. Results of oscillographic measurements, to be described in detail in a following section, show that no reignition occurs at contact speeds above 1.7 inches per second, but that reignition may occur at a speed of 0.024 in. per sec.

The establishment of a critical contact speed at which the minimum arc energy is obtained is interesting theoretically and may have considerable practical value. As the current is increased the critical contact speed becomes higher, showing that with larger currents reignition begins to take place at larger gaps. Additional data obtained with currents up to 100 amperes would

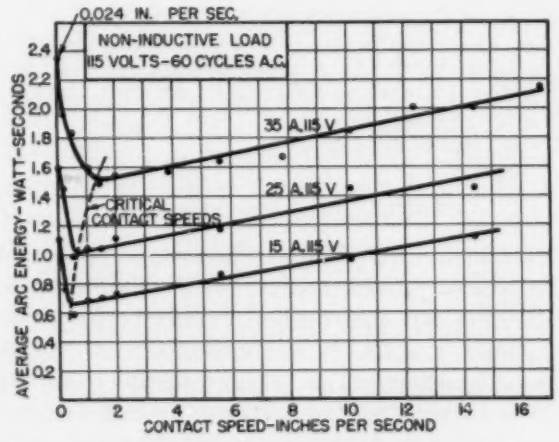

Fig. 2. Curves showing the effect of contact opening speed on average arc energy. Each point of these curves represents the average of 300 individual readings.

[7] T. A. Rich and E. J. Hatfield, Jr., "The Ballistic Wattmeter," Gen. Elec. Rev. **41**, 288–293 (1938).

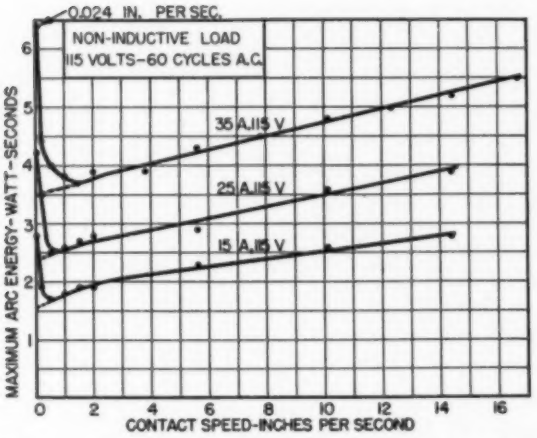

FIG. 3. Curves showing the effect of contact opening speed on maximum arc energy obtained at three current values.

make it possible to establish a more general relation between contact speed and current for minimum arc energy.

The extent of reignition (number of half-cycles in which reignition occurs) was determined by selecting the highest values of arc energy obtained at each speed and plotting these against the contact speed. Curves thus obtained for the three currents used are shown in Fig. 3. By extending the high speed sections of these maximum arc energy curves to the lowest contact speed, values of arc energy are shown which would be expected if the arc persisted for one half-cycle only. The ratios of the actual maximum arc energies to the values obtained by extending the high speed sections of the curves indicate the extent of reignition at the lowest speed at which tests were conducted. The ratios thus obtained are given in Table I, and indicate that on 115 volts reignition did not take place beyond the second half-cycle.

EFFECT OF LINE VOLTAGE

To further investigate reignition by means of arc energy measurements, tests were made on 225 volts and the results compared with those run on 115 volts. It was expected that at the lowest speeds more arc energy should result on 225 volts than on 115 volts due to more reignition. This actually took place at the 0.024-inch-per-second speed as shown in Table II, where the average arc energies are compared at three different contact speeds and for two currents on both 115 and 225 volts.

That the extent of reignition was greater on 225 volts than on 115 volts is evident from the data of Table III. The ratio of the maximum arc energy at a speed of 0.024 inch per sec. to that at 1.5 inches per sec. has a value of 3 on 225 volts, indicating the possibility of current flowing in the arc for three half-cycles, whereas on 115 volts only two half-cycles of current flow were obtained at most.

TABLE I. *Extent of reignition at 115 volts. Contact opening speed = 0.024 in. per sec. Fine silver contacts. Noninductive load.*

CURRENT	ACTUAL MAXIMUM ARC ENERGY FIG. 3	MAXIMUM ARC ENERGY BY EXTENDING STRAIGHT LINE[a]	RATIO OF ACTUAL TO EXTENDED ARC ENERGIES[b]
15 amperes	2.8 joules	1.6 joules	1.75
25	4.2	2.4	1.75
35	6.4	3.5	1.83

[a] The values of arc energies obtained by extending the straight line to the lowest speed are those as if no reignition took place.
[b] Ratios indicate that the longest arcing time was equal to or less than two half-cycles of 60-cycle current.

CALCULATION OF ARC ENERGY

In analyzing results of arc energy measurements with the ballistic wattmeter, it is often desirable to be able to calculate the arc energy when the variables are known or can be closely estimated. The most important variable is the arc voltage. With contacts opening at high speeds, the arc voltage depends on the speed, but the exact relation is not available. If the contact opening speeds are sufficiently slow, so that the arc gap is small and has no appreciable effect on the arc voltage, the arc energy calculations are considerably simplified. In this case the arc voltage can be closely estimated if the initial potential for the contact material is known, since this is the lowest value the arc voltage can have.

The initial potential which arises between two copper electrodes when they are separated to form an arc has been accurately determined. Betz and Karrer[8] have informed the present writer that this potential for silver is about one volt higher than for copper, so that for a silver arc it is probably about 13.2 volts. Values of the arc voltage at the start of arcing as determined

[8] Paul L. Betz and S. Karrer, "A Characteristic of the Copper Arc During the Formative Period," J. App. Phys. 8, 845–848 (1937).

in the present investigation are given in Table IV, the average at all currents and speeds being 14.8 volts.

For purposes of illustration, the calculation of arc energy for a representative break is shown. Fig. 4 is an oscillogram taken at a contact speed of 0.024 inch per second and 16.3 amperes r.m.s. current. The standard expression for arc energy will be used as follows:

$$W_a = \frac{2}{\pi} i_m \bar{v}_a t \qquad (2)$$

where i_m = maximum current in the cycle, $\bar{v}_a$ = mean arc voltage, t = arcing time.

The factor $2/\pi\, i_m$ gives the mean value of the current and is obtained by considering the current as a sine wave. Using values of 18 volts for arc voltage, 21.2 amperes for current and 0.007 second for the arcing time, the arc energy from (2) is 1.7 joules. As a check, the energy from the power record was calculated by measuring the area under the power curve and multiplying it by the power and time constants. The energy thus obtained is 1.55 joules. The difference in these two results is due to the value of arc voltage used, which in this case is lower at the instant when the current is a maximum than at the start of arcing. The oscillogram for this case illustrates the negative characteristic of the arc, the arc voltage decreasing as the current increases. The arc voltage at the instant of maximum current is 14.6 volts, and if the average of this and the arc voltage at the start is used, the arc energy from Eq. (2) is 1.54 joules, giving an excellent agreement with the measured value by means of the oscillograph. The agreement with measurements with the ballistic wattmeter is also very good, the value for these approximate conditions being 1.6 joules.

TABLE II. *Comparison of arc energy measurements on 115 and 225 volts. Fine silver contacts.*

Current	Voltage	Contact Speed	Average Arc Energy	Ratio 225 : 115
35 amp.	115 volts	1.45″/sec.	1.49 joules	
35	225	1.51	1.43	0.96
35	115	0.19	1.97	
35	225	0.20	1.89	0.96
35	115	0.024	2.36	
35	225	0.024	3.75	1.59
15	115	1.51	0.71	
15	225	1.51	0.75	1.06
15	115	0.20	0.77	
15	225	0.20	0.78	1.01
15	115	0.024	1.11	
15	225	0.024	1.64	1.48

TABLE III. *Maximum arc energies on 225 volts at different contact speeds. Fine silver contacts.*

Contact Speed	Maximum Arc Energy	Ratio of Energy at 0.024″/sec. Speed to 1.5″/sec.
1.5″/sec.	3.9 joules	—
0.20	4.3	—
0.024	11.9	3.06

Ratio indicates that longest arcing time was of the order of three half-cycles of 60-cycle current.

Oscillograph Measurements

The results of arc energy measurements with a ballistic wattmeter are very useful in establishing the gross effect of different variables involved in a.c. arcing, but for a more detailed study independent measurements of the arcing time, arc voltage and current are necessary. These were obtained with an oscillograph having in addition to the usual current and potential elements, a watt element for the recording of the arc power. Oscillographic measurements were made with currents of 16 and 34 amperes, 120 volts, 60 cycles. Altogether 44 oscillograms were taken at three representative contact speeds: 0.024, 1.7 and 16.7 inches per second.

The analysis of these oscillograms showed that no reignition occurred when the contacts were separated at speeds of 1.7 or 16.7 inches per second. It was found that with contacts separated at the speed of 0.024 inch per second reignition occurred, but not at every break. Actually, on 34 amperes, seven cases of reignition occurred in 14 operations, while on 16 amperes only one reignition took place in six operations. These ratios might be different if a larger number of breaks

TABLE IV. *Arc voltage with silver contacts.*

Contact Opening Speed	Arc Voltage at Start Average for 16 and 34 amp.
16.7 inches per sec.	13.9 volts
1.7	15.0
0.024	15.7

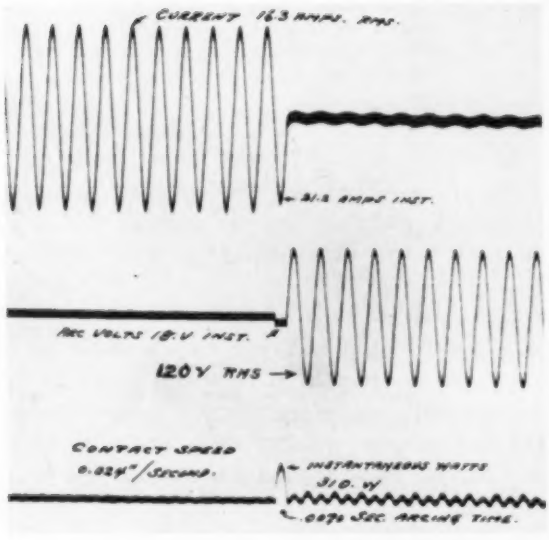

FIG. 4. Oscillogram used in illustrating the calculation of arc energy. The arc voltage record shows the negative characteristic of the arc.

were examined. Oscillograms of Fig. 5 show that with an exactly identical current at the instant of the start of contact separation and the same gap when the current became zero, reignition occurred in one case and not in the other. In the left-hand oscillogram of Fig. 5 a case is shown of reignition at a potential of 85 volts. The other extreme is shown in the oscillogram of Fig. 6 where reignition occurred at the peak of the voltage wave.

THEORY OF REIGNITION*

The mechanism leading to the reigniting of an arc between slowly separating contacts in low voltage a.c. circuits is quite different from that for reignition in high voltage, low power factor circuits. In the latter case, for metal electrodes having high thermal conductivities and low boiling points, gases at atmospheric pressure are able to withstand potentials of the order of 200 volts applied instantaneously across the gap. At higher potentials the arc which forms is preceded by a low current glow discharge, the minimum potential required being in the neighborhood of the cathode fall for the glow state. The present experiments clearly show that the maximum line potential of 170 volts in the 120-volt circuit is

* I am indebted to Professor W. S. Huxford for calling to my attention the possibility that field emission of electrons is responsible for arc reignition in these very short gaps.

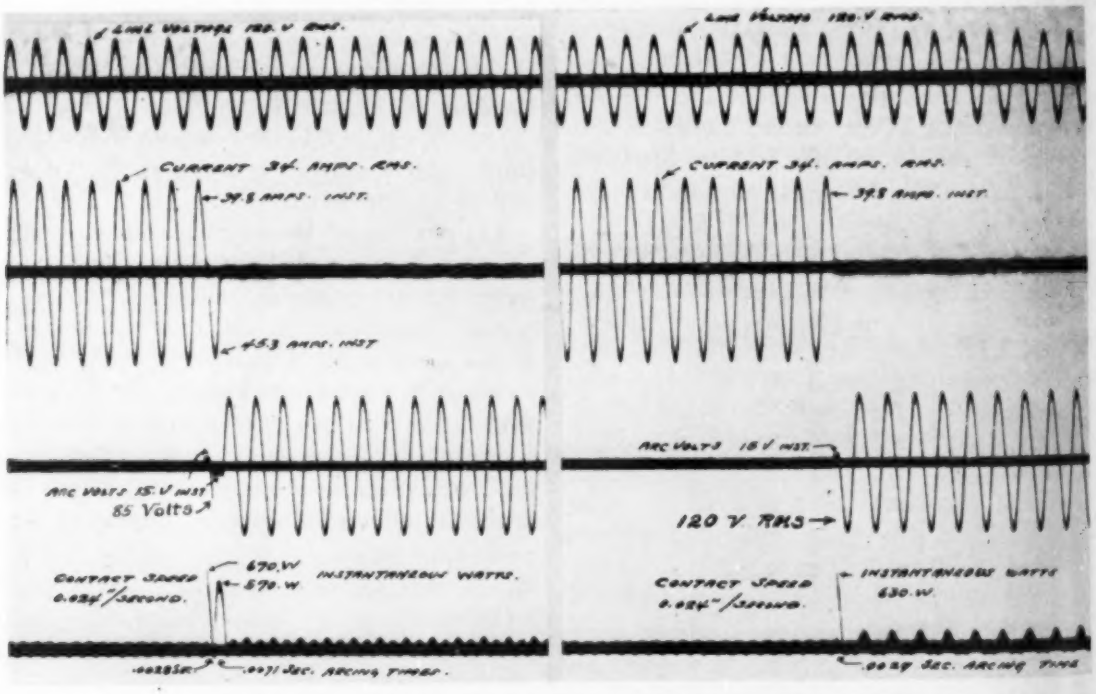

FIG. 5. Oscillograms showing that, with identical circuit conditions at the instant the contacts were opened, reignition took place in one case and not in the other. The oscillogram at the left shows reignition occurring at a potential of 85 volts.

TABLE V. *Potential and field strength at instant of reignition. Contact opening speed = 0.024 inch per second.*

CURRENT	POTENTIAL	FIELD
34 amperes	72 volts	0.19×10^6 volts per cm
34	85	0.35×10^6
34	154	0.31×10^6
34	165	0.37×10^6
34	170	0.28×10^6
34	170	0.29×10^6
16.3	165	0.30×10^6

not sufficient to break down the gap if the contacts are separated at speeds greater than 1.5 in. per sec., a result in agreement with current theories of restriking. In fact, since restriking did not occur at these speeds on 225 volts a.c., the reignition potential for silver electrodes must be greater than 317 volts, which is the potential across the gap a quarter of a cycle after current zero. Restriking at low speeds obviously depends, therefore, upon factors not usually considered in connection with the problem of a.c. circuit interruption.

In the absence of potentials high enough to initiate a glow discharge some other means of supplying electrons and ions must exist to provide the cathode conditions required for an arc. The low rate of rise of potential between the contacts following extinction of the arc does not favor a continuation of the discharge. Due to the very small electrode separations at low speeds the temperature of the gases in the arc column rapidly decreases, thermal ionization ceases after a few microseconds and the ions quickly disappear by recombination on the electrode surfaces. Any new discharge set up must be initiated by a new supply of electrons, and the most likely source is the surface of the cathode terminal.

At a contact speed of 0.024 inch per sec., the electrodes are 0.0005 cm apart at a time equal to a half-current cycle after separation begins. Values of the electric field in the gap obtained by dividing the potential shown on the oscillograph trace by the contact separation when reignition occurs are high enough to produce autoelectronic emission from a metal. In Table V are given the potentials and fields for seven cases of reignition observed in the oscillographic study. In these seven cases the average field value at the instant of reignition was $0.30\cdot10^6$ volts/cm. Many investigators have observed appreciable field currents of electrons at values of field of this order from unpolished metal surfaces subject to gas charging at atmospheric pressure.[9] A number of years ago Earhart[10] discovered that a spark discharge occurred at low potentials between polished metal spheres at separations up to 2 microns, that this spark did not have a time lag, and was critically dependent upon the electric field. The field required was constant for a given metal, and for the several metals investigated varied from 1 to $2\cdot10^6$ volts/cm. It thus appears quite certain that a necessary condition for restriking of the arc in a gap space of a few microns is the existence of fields large enough to extract electrons from the metal electrode.

Evidently conditions other than the existence of a field sufficient for autoelectronic emission contribute to the establishment of an arc, since in 14 trials where the fields were high enough for this to take place only seven resulted in arc reignition. In the absence of appreciable ion concentration in the gap, field electrons will lead to formation of an arc provided they are able to ionize gas or vapor molecules in sufficient numbers to establish the normal cathode fall region. At large electrode separations the field required

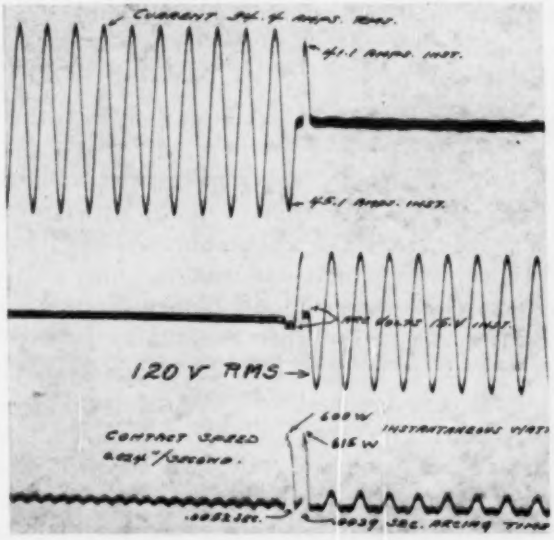

FIG. 6. Oscillogram showing long period of zero current prior to reignition. In this case the arc restruck at approximately the peak voltage of 170 volts.

[9] J. W. Flowers, Phys. Rev. **48**, 954 (1935); F. M. Penning and J. G. W. Mulder, Physica **2**, 724 (1935).
[10] Earhart, Phil. Mag. **1**, 147 (1901); Hobbs, Phil. Mag. **10**, 617 (1905).

to supply electrons to the arc is established at the cathode surface by the formation there of a dense ion sheath. A second condition, then, for arc reignition is a rapid accumulation of sufficient ions at the cathode to set up the minimum current density required for maintenance of a field arc.

Several factors undoubtedly contribute to the probability of arc reignition. The roughness of the contact surfaces determines to a large extent the value of the local fields, and this changes with continued opening and closing of the circuit. The charging of the metal with gas during the previous arcing will not occur in a uniform way, and the work-function of the electrode surfaces will vary considerably from point to point. These, together with variations in metal vapor concentration in the space, probably account for the statistical nature of the results obtained for arc reignition at low contact speeds. The study is being continued to determine the effect of these various factors and to measure the extent of reignition at still lower speeds as a function of the value of the current which is being interrupted.

Acknowledgment

The writer is very grateful to Mr. W. J. Ettinger of the Edison General Electric Appliance Company for his encouragement and interest, to Professor W. S. Huxford of the Physics Department, Northwestern University, for continual and generous help, and to Mr. J. C. Sharp, Chief Engineer of the Edison General Electric Appliance Company, for making this research possible and for permission to publish the results.

Beam Tubes as Ultra-High Frequency Generators

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(Received February 4, 1939)

The operation of beam power tubes in regenerative ultra-high frequency oscillators is investigated experimentally. Wave-length characteristics of oscillating 6Y6-G and 6V6-G tubes are displayed and compared with a corresponding curve for a type 56 triode. Wave-lengths as low as 150 cm were obtained. Current and wave-length characteristics of the oscillating 6Y6-G are given as functions of plate, screen and control grid voltages. The efficiency of the generator is investigated near its lowest wave-length limit. Means for preventing oscillation in amplifier circuits using beam tubes are suggested.

IN recent papers[1, 2] the characteristics of beam tubes were discussed in detail with special reference to the requirements of power amplifiers. Although brief comments were included on the use of these tubes in oscillatory circuits, no mention was made of their remarkable properties as generators of ultra-high frequency currents. A short time ago, and from two independent researches in progress in this laboratory, the writer's attention was called to the fact that beam tubes of the types, 6Y6-G, 6V6-G, 6L6-G, all support parasitic oscillations of great intensity when connected in apparently conventional amplifier circuits and operated at rated voltages. In fact, the oscillations persisted under such diverse conditions, that it seemed to be a real problem to eliminate them in circuits in which they were not desired. It was primarily in order to devise means for preventing the generation of these troublesome ultra-high frequency currents that the present study was undertaken. However, after a preliminary series of experiments had revealed the rather unusual qualities of the beam tubes for sustaining such currents, a more detailed investigation seemed desirable.

The suggestion, that the oscillations, which occur primarily in the screen-plate circuit, might be explained in terms of space charge oscillations of the Barkhausen and Kurz type, was quickly disproved. Although they were originally discovered with the screen and plate at the same potential, it was subsequently shown that they could be maintained at screen voltages which ranged from −40 volts to values well above the

[1] Salzberg and Haeff, RCA Rev. **2**, 336 (1938).
[2] O. H. Schade, Proc. I. R. E. **26**, 137 (1938).

plate potential in the case of the 6Y6-G. Furthermore, oscillations were not supported with the plate negative. From these observations it was concluded that the beam tube oscillator was of the simple regenerative type familiar in triode circuits, but with the screen taking the part of the grid in the triode. This conclusion was completely verified when it was found that the wave-length characteristics of the beam tetrode as functions of the tank circuit dimensions were precisely like those of the triode in a simple regenerative circuit. For this reason it seems desirable to review briefly the characteristics of such a triode oscillator.

Wave-Length Characteristics of a Triode Oscillator

The fundamental frequency equation of an oscillatory circuit consisting of a section of parallel rods of length, s, bridged at one end by a large capacitance and connected at the other end to plate and grid of a triode, has been shown to have the following form.[3]

$$\omega \tan (\omega s/v) = 1/Z_c C_t. \tag{1}$$

Here v is the velocity of propagation along the parallel rods of characteristic impedance, Z_c, and length, s. The effective capacitance, C_t, between plate and grid is defined below.

$$C_t = C_1 + C_2 C_3/(C_2 + C_3). \tag{2}$$

The interelectrode capacitances are, C_1: plate-grid; C_2: cathode-grid; C_3: cathode-plate. Using a 56 tube connected to a parallel line consisting of rods of diameter, 0.5 cm and separation, 2.8 cm, one has the following numerical values.

$$C_1 = C_2 = 3.2 \text{ mmf}; \qquad C_3 = 2.2 \text{ mmf} \tag{3a}$$

$$C_t = 4.5 \text{ mmf} \tag{3b}$$

$$Z_c = 289 \text{ ohms}. \tag{3c}$$

Upon substituting these numbers in (1) and using the relation,

$$\omega = 2\pi f = 2\pi v/\lambda, \tag{4}$$

the theoretical wave-length characteristic shown in Fig. 1 was computed. The theoretical asymptote and the equivalent length, s', of the triode capacitance, C_t, are also shown. This latter is calculated from the relation,[3]

$$s' = C_t/c. \tag{5}$$

Here c is the capacitance per unit length of the parallel rods. The experimentally determined wave-length characteristic is shown plotted in Fig. 1. It is seen to coincide with the theoretical curve for sufficiently large values of s, but it falls below it for shorter lengths corresponding to the higher generated frequencies. Superficially it might be supposed that the discrepancy for short lengths, s, of the tank circuit might be attributed to the fact that the leads within the tube were neglected, so that the triode was assumed to be a circuit consisting simply of three lumped interelectrode capacitances. A little reflection reveals, however, that the leads running into the tube, themselves constitute a section of parallel line, to be sure of quite different characteristic impedance from that of the external tank circuit. Nevertheless, the principal effect of taking the leads into account is a small shift to the left of the origin of the coordinate, s, in Fig. 1, both for the theoretical and for the experimental curve. An additional small shift of about a centimeter would have to be made if the equivalent length of the bridging condenser were taken into account. The effect of such shifts evidently is not to change the relative positions of the curves.

A more promising explanation for the smaller generated wave-lengths in the experimental curve may be found in the fact that the numerical values of the interelectrode capacitances listed in (3a), (which were used in computing the theoretical curve of Fig. 1 from formula (1)), are for a

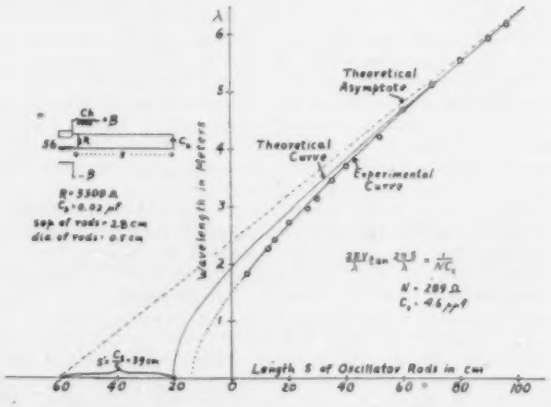


Fig. 1. Theoretical and experimental wave-length characteristics of a triode.

[3] R. King, Proc. I. R. E. **20**, 1371 (1932).

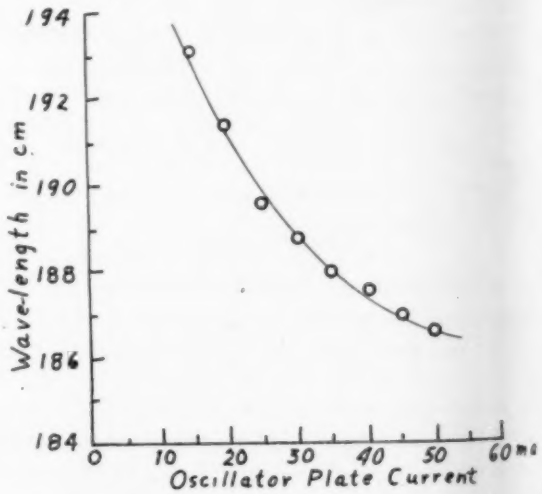
cold tube containing no space current of electrons between cathode and anode. Muhrer[4] and others[5] have shown that the effect of a stream of free electrons between the plates of a condenser is to decrease the effective capacitance. Muhrer's measurements showed a decrease by as much as 50 percent in the capacitance for the case of small high frequency voltages superimposed upon the steady electrode potentials.[6] Although the assumption, that only small high frequency voltages be impressed across the capacitance in question, is presumably not satisfied in the case of the oscillator in which ultra-high frequency voltages of considerable amplitude may be maintained across the grid-plate space, the conclusion that the space current diminishes the effective capacitance does lead to a frequency correction in the right direction. It is clear that since the plate-grid capacitance is a significant part of the tank circuit, especially at short lengths of parallel rods, a change in C_t, which depends primarily upon the plate-grid capacitance, involves a corresponding change in the generated frequency. From Eq. (1) it follows that a decrease in C_t demands an increase in ω, and hence a decrease in λ. It is also evident, however, that such a decrease will be significant only for the shorter wave-lengths associated with small lengths, s. In this case (1) approaches the parabola,

$$\lambda^2 = s(C_t/4\pi^2 c). \tag{6}$$

For large values of s, on the other hand, C_t plays a smaller and smaller part in determining ω as s increases. Consequently a change in C_t due to space charge will have a diminishing effect on λ as s becomes larger. It follows, therefore, that the theoretical curve in Fig. 1 will be distorted by a decrease in C_t in precisely such a way as will bring it nearer the experimental one. A smaller C_t necessarily also means a smaller equivalent length, s', as defined in (5), so that the theoretical asymptote would also be moved to make it more nearly tangent to the experimental curve.

The effect of space charge in increasing the generated frequency by effectively decreasing the interelectrode capacitances is also verified in Fig. 2 in which the generated wave-length of a triode oscillator is plotted as a function of the plate current. It is clear from this curve, that as the space current increases the generated wave-length diminishes just as would be predicted in terms of a decreasing capacitance between grid and plate as the space charge density increases.

After these preliminary remarks on the properties of a triode oscillator of a simple regenerative type, one can turn to the more complicated, but fundamentally similar beam tube oscillator.



FG. 2. Wave-length variation with plate current in a triode oscillator.

[4] E. Muhrer, Hochfrequenztech. u. Elektroak. **43**, 1 (1934).

[5] H. E. Hollmann, *Physik u. Technik der ultrakurzen Wellen* (Springer, 1936), Vol. 1, pp. 116, 118.

[6] There appears to be considerable uncertainty in the literature regarding the effect of a space current on the interelectrode capacitances of a triode. Llewellyn (Bell. Syst. Tech. J. **15**, 575 (1936), for example, states that in the delta-network of a negative grid triode, which he suggests for use at moderately high frequencies, the cathode-grid and the cathode-plate capacitances are larger, the grid-plate capacitance smaller when the space current flows than when the tube is cold. Benham (Proc. I. R. E. **26**, 1104 (1938), on the other hand, disagrees with Llewellyn's conclusion regarding the plate-grid capacitance. He maintains that all three interelectrode capacitances must be effectively larger when the electron stream flows than without it, except when the tube is under load. He asserts that the effective capacitance is a function of the load. Experimental results by Jones (J. I. E. E., London **81**, 658 (1938) seem to confirm a decrease in grid-plate capacitance even at no load. It is not clear whether these contradictions may be ascribed entirely to differences in definition or primary assumption, or whether fundamental difficulties are involved. For present purposes it is sufficient to note that the conditions assumed by Muhrer and the actual experimental arrangement he used, correspond quite closely with the case of a triode oscillator in which the plate-grid capacitance forms an essential part of the tank circuit. The chief difference between the two cases lies in the fact that Muhrer impressed oscillations of small amplitude from an external source on a resonant circuit, whereas in the case of the oscillator, the oscillations were self-excited and not always of small amplitude compared with the steady applied potentials.

Wave-Length Characteristics of a Beam Tube Oscillator

The fundamental structural differences between a beam tetrode, such as the 6Y6-G, and an ordinary screen grid tube have been described at length in the literature.[2] Of special importance is the fact that the screen grid wires are so wound that they lie in the shadow of the control grid wires, so that the electron streams passing through the control grid spaces on their way to the plate, are focused through the screen grid spaces. This means that the screen may be operated at high potentials while yet drawing a very small current, provided an appreciable number of electrons does not return to the screen from the plate-screen space as a result of the formation of a virtual cathode in that space. A significant characteristic associated with the formation of such a virtual cathode, is a sudden change in the potential and charge distribution when the space current exceeds a certain critical value at which the potential minimum in the plate-screen space abruptly drops to zero to form a virtual cathode, and this in turn promptly shifts toward the screen.[7] The space current for which the shift occurs is not quite the same when the current is increased as when it is decreased. Since the two values overlap, a loop appears in the characteristic.

In order to obtain wave-length characteristics of the beam tubes similar to the triode curve of Fig. 1, the circuit shown in Fig. 3 was used. The

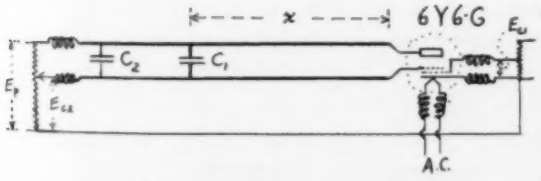


Fig. 3. Circuit of a beam tube oscillator.

tank circuit consisted of a length, x, of parallel brass rods connected at one end to the plate and screen terminals of the beam tube, and bridged at the other by a large blocking condenser, C_1 (Fig. 3). A second condenser, C_2, served to detune the length of rods extending beyond C_1. All battery connections to the control grid, the cathode, the heater and the tank circuit were

[7] See reference 1, p. 354.

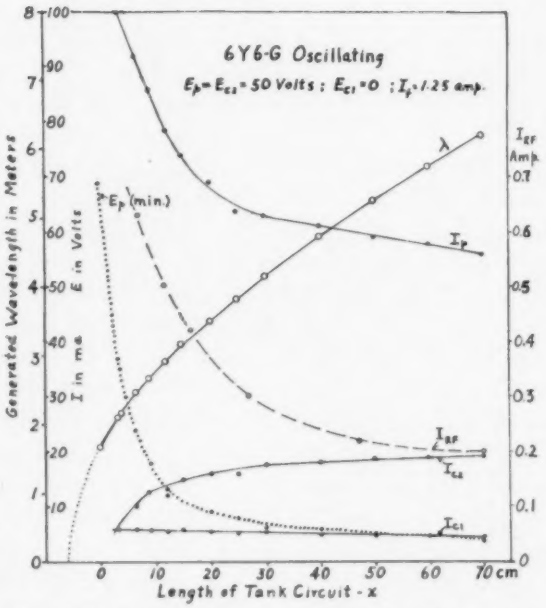


Fig. 4. Wave-length characteristics of the 6Y6-G tube.

provided with adjustable coils which were kept arranged to act as parallel resonance wave traps. When it was desired to read the ultra-high frequency current in the tank circuit, a thermal ammeter or thermocouple was connected in series with C_1. For operation with plate and screen at the same potential, the blocking condenser, C_1, could be dispensed with. For the shortest possible length, x, a piece of heavy wire was connected directly across the screen and plate terminals of the wafer socket, and the brass rods and bridging condensers were not used. The generated wave-length was measured on a parallel wire system which was loosely coupled to the tank circuit. The wave-length and current characteristics of the 6Y6-G shown in Fig. 4 were obtained by increasing the length, x, in steps and taking the necessary current and wave-length calibration readings for each. The plate and screen were operated at the same potential in the calibrations, and this voltage was chosen well below the maximum rated value for the particular tube.

A comparison of the wave-length curve of the beam tube plotted in Fig. 4 with the triode curve shown in Fig. 1, indicates that they are entirely alike. The only differences arise from the fact that the characteristic impedances of the tank circuits and the effective tube capacitances, C_t, were not alike. Curves marked E_p(min) are also

shown in Fig. 4. They indicate the lowest plate and screen voltage at which oscillations were maintained for the particular length, x, of the tank circuit. From these it is clear that oscillations are supported over an exceedingly wide range of potentials, except at the lowest generated wave-lengths. It is to be noted that in spite of the relatively large size of the electrodes in the beam tubes, the upper frequency limit for both the 6Y6-G and the 6V6-G is about the same as that of a small triode like the 56. (The lower wave-length limit of the much larger 6L6-G is near 4.5 meters.) The explanation for this fact lies in the construction of the tubes. As a result of the shielding of the beam-forming plates between plate and screen, the area of the plate exposed to the screen in the 6Y6-G is not much greater than the plate area exposed to the grid in the cylindrical 56. Since the average distance between plate and screen in the beam tube is nearly double that in the triode, it is clear that the effective plate-screen capacitance of the former can not be larger than the plate-grid capacitance of the latter. Without attempting to compute C_t for the tetrode (the formula is necessarily much more complicated than (3)), it seems

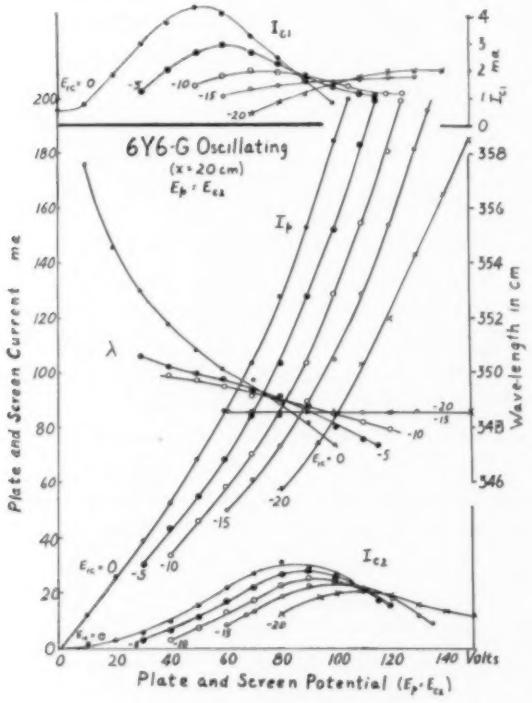


FIG. 5. Characteristics of the 6Y6-G.

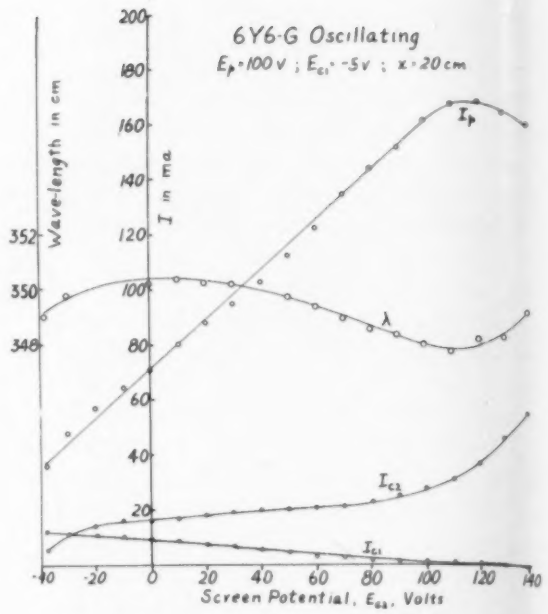


FIG. 6. Characteristics of the 6Y6-G.

entirely reasonable that it should be no larger for the 6Y6-G than for the 56.

In Figs. 5 and 6 current and wave-length characteristics of the oscillating 6Y6-G tube are shown for a fixed tank circuit of moderate length. The variables and parameters are the plate, screen and control grid voltages. In Fig. 5 the wave-length is seen to decrease with rising space current much as in the case of the triode characteristic drawn in Fig. 2. This decrease may again be explained in terms of a lowering in the effective plate-screen capacitance as a result of increasing space charge density. In Fig. 6 the decrease in wave-length for screen voltages ranging from zero to a voltage equal to that of the plate, i.e., 100 volts, may also be interpreted in terms of a decreasing capacitance with increasing space current. The abrupt rise in wave-length as the screen voltage is allowed to exceed the plate voltage, may be ascribed to a decrease in space current density in the plate-screen space as the plate current diminishes and the screen begins to take a rapidly increasing share of the space current. Due to the fact that the current from the cathode is focused through the screen spaces by the control grid wire alignment, one must conclude that a large part of the screen current returns to the screen after entering the plate-screen space. This would occur during the positive half-

cycle of the screen, when the reverse gradient in the space between plate and screen must be quite large. The decrease in wave-length shown in Fig. 6 as the screen becomes negative, may be made plausible as follows. With the screen negative the velocity of the electrons entering the screen-plate space is necessarily much smaller than with the screen positive. Consequently the transit time across the screen-plate space must be increased, and in this way the average space charge density increased. The accompanying decrease in screen-plate capacitance should produce a smaller generated wave-length.

The effect of the control grid bias on the charge density distribution, and hence on the wave-length generated is not so simply explained. From the curves of Fig. 5 it is clear that for fixed plate and screen voltages at some value below about 70 volts, the effect of increasing the space current by decreasing the negative control grid bias, is to increase the wave-length. On the other hand, for plate and screen voltages fixed at some value above 90, the effect of increasing the space current in precisely the same way is exactly the reverse, the wave-length is decreased. It is to be noted that the latter effect at higher space currents agrees with the results obtained by increasing the space current by increasing plate and screen voltages at fixed grid bias. Since it does not seem reasonable to suppose that the space current distribution is very different in the screen-plate space when the control grid is slightly negative and screen and plate correspondingly slightly more positive to yield the same current, one must conclude that it is not a change in the charge density in the screen-plate space, but in the cathode screen spaces which produces the change in C_t and hence in the wave-length. A change in the cathode space charge region due to negative bias on the control grid should be more effective at low space current than at high, when the negative bias is less significant compared with the large screen and plate voltages.

Superficially it appears that the attempt to explain the change in wave-length generated by a beam tube oscillator with a fixed tank circuit in terms of a change in the effective capacitance with space current density is at least qualitatively successful. On the other hand, it may well be that the extremely complicated potential and charge density distributions in a beam tetrode when generating an ultra-high frequency voltage in a tank circuit of which its interelectrode capacitances are an essential part, cannot be treated in so simple a way. Unfortunately the mathematical problem of calculating the potential and space current distributions even of a triode have thus far been insurmountable for the case of large high frequency voltages between the electrodes. In order to further illustrate the actual complexity of this problem, and at the same time display an important and interesting set of characteristics, the case of the same tube oscillating nearer its lower wave-length limit was investigated experimentally. The external circuit in this case consisted merely of a thermocouple and a blocking condenser attached directly across the plate and screen terminals of the 6Y6-G. The difference in behavior at this lower wave-length lies in the fact that a discontinuity occurs in the characteristics. This may, presumably, be associated with the sudden shift from a potential minimum to a virtual cathode in the screen-plate space as the space current ex-

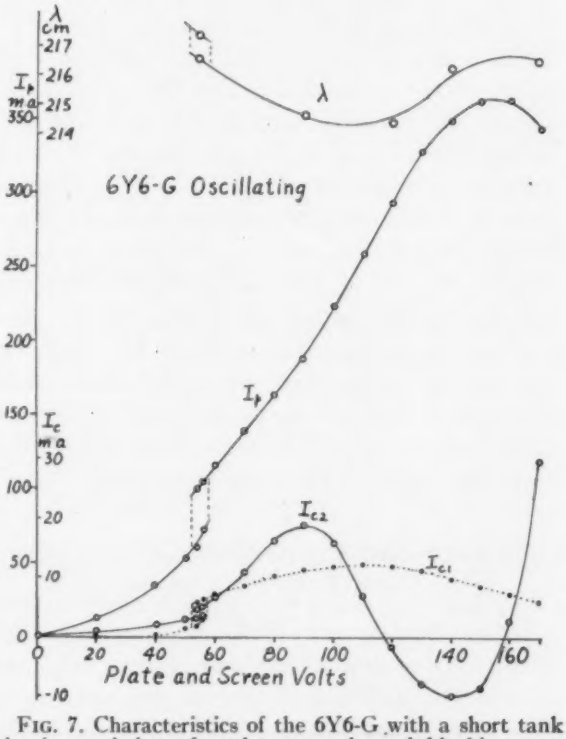


FIG. 7. Characteristics of the 6Y6-G with a short tank circuit consisting of a thermocouple and blocking condenser only in addition to the tube and its socket.

ceeds a critical value. Since the amplitude of the ultra-high frequency oscillation is quite low when the discontinuity appears, it seems safe to assume that the steady conditions, under which such a shift is known to occur, obtain at least approximately. It may be remarked that as the external tank circuit is lengthened, and the generated wave-length increases, the discontinuity occurs at lower and lower plate and screen voltages, and its magnitude rapidly diminishes. Consequently, for a tank circuit longer than about five centimeters no trace of a break in the characteristics appears. In Fig. 7 the current and wave-length characteristics of the 6Y6-G are shown when oscillating with a fixed tank circuit having a resonant wave-length near 215 cm. The abrupt and overlapping discontinuities in all curves are conspicuous. An examination of the screen current curve reveals a rapid rise in screen current after the change, such as would be expected if a virtual cathode were formed between screen and plate to turn back a greater number of electrons to the screen. The drop in the wave-length also indicates a decrease in the effective plate-screen capacitance due to an increase in average charge density, such as might be expected to occur when a virtual cathode is formed with all other conditions relatively unchanged. It is clear that, if this theory is correct, the virtual cathode must move back and forth between plate and screen periodically. Presumably as a result of the high reverse electron current bombarding the screen from the plate-screen-space during the positive half-cycle of the screen, this begins to emit secondary electrons and finally becomes incandescent as the plate and screen voltage is increased. The high frequency current in the tank circuit then begins to decrease. Oscillations do not break off until the plate becomes quite red. This occurs between 170 and 180 volts on both plate and screen.

Power Output and Efficiency of the Beam Tube Oscillator

In speaking of the efficiency of an ultra-high frequency oscillator of both the triode and tetrode types described above, one must carefully distinguish between the efficiency of the circuit in terms of high frequency power developed in the entire tank circuit or radiated from it, and the efficiency in terms of the high frequency power supplied to that part of the tank circuit which is outside of the tube bulb. For short external circuits, such as are required at the higher frequencies, the latter may well be only a small fraction of the total power converted. From the practical point of view of determining the power available for an antenna or other load, one is naturally interested only in the power developed in the external part of the tank circuit, since the ultra-high frequency power consumed in the tube is wasted as heat. On the other hand, in determining the efficiency of the circuit as a power converter, one is concerned with the total high frequency power developed in the entire tank circuit. It is to be noted that by changing the design of the tubes especially for use at ultra-high frequencies, a considerable shortening of the leads within the bulb is possible, and the wire size (which is ridiculously small for ultra-high frequency currents of several amperes) can be very much increased. If this were done the major part of the total power converted into ultra-high frequency form should be available in an external circuit.

If one is interested primarily in the efficiency of the beam tube oscillator in terms of power available in the external part of the tank circuit, methods of measuring the total heat developed per second in the tube may be used for determining the wasted power. If it is a question of obtaining, in addition, a measure of the efficiency of the entire device as a power converter, such methods cannot be used because the ultra-high frequency power consumed in that part of the tank circuit contained in the tube also appears as heat. What is required is a method for measuring the total power absorbed in and radiated from the entire tank circuit at or near its natural frequency. Such a method evidently involves measuring the effective resistance (Ohmic and radiation) of the tank circuit at a frequency and with a current distribution corresponding closely to those obtaining when the tube is oscillating. It is possible to measure this resistance by removing the glass bulb, attaching short connections directly to the plate and screen, and then using the entire tank circuit between these connections as a bridge on a parallel wire system.

Following a method devised by the writer[8] it is possible to measure the effective ultra-high frequency resistance of such a bridge. It is to be noted especially that using the entire tank circuit as a bridge with connections directly to plate and screen, leads to a current amplitude distribution which is essentially the same as that obtaining in the same circuit when oscillating, provided the parallel wire system is excited by a frequency very near the natural frequency of the tank circuit to be measured. When the bridge is moved along the wires until a maximum deflection is recorded in the voltmeter at the opposite end, an ultra-high frequency voltage is impressed across the screen-plate space of the tube, and a current maximum will obtain in the thermal ammeter or thermocouple connecting the plate and screen terminals of the socket. Care must, of course, be exercised to use a correctly adjusted tandem bridge with the tank circuit bridge as explained in reference 8, Part II. The effective resistance between the screen and plate of the tank circuit, as measured in terms of the decrease in amplitude of the standing wave on the parallel line, evidently includes all power losses in the bridge whether in the form of heat or radiated energy. Since it is desired to determine the efficiency of the beam tube oscillator near its lower wave-length limit, the short tank circuit consisting only of tube, socket, blocking condenser and thermocouple was used. This is the same circuit as was used in obtaining the characteristics of Fig. 7.

It has been shown[9] that the ratio, p, of two voltmeter deflections (corrected for linear scale as explained in reference 8, Part II) for two different bridges (distinguished by primes and double primes) adjusted to resonance on a parallel line is given by:

$$p=V_0'/V_0''=\frac{\alpha s''+\rho_0+\rho_s''}{\alpha s'+\rho_0+\rho_s'}. \tag{6}$$

Here, $\rho_0=g_0/(1+b_0^2)$; $\rho_s=g_s/(1+b_s^2)$ (7)

and $g_0=Z_cG_0$; $g_s=Z_cG_s$ (8a)

$b_0=Z_cB_0$; $b_s=Z_cB_s$. (8b)

In the above expressions α is the effective damping constant of the line defined by

$$\alpha=r/2Z_c \tag{8c}$$

with r the effective resistance per loop unit length. Z_c is the characteristic impedance of the line; s is its length between the bridge and the voltmeter. G_0 and B_0 are, respectively, the conductance and susceptance of the voltmeter; G_s and B_s are the conductance and susceptance of the bridge. For the case of small reactance in the bridge, such as obtains both in short pieces of straight wire and in a tank circuit which is near resonance at the measuring frequency, one may write

$$b_s^2\ll 1, \tag{9}$$

so that

$$\rho_s\doteq R_s/Z_c. \tag{10}$$

Here R_s is the effective resistance of the bridge at the frequency concerned. It has been pointed out, and it is readily verified experimentally, that because the reactances of both wire bridges and of a bridge consisting of the tank circuit of the beam tube oscillator are small, they produce resonance in the parallel line when placed at about the same distance from the voltmeter. That is, s' and s'' in (6) are nearly the same for wire bridges and for the tank circuit bridge. Since the voltmeter is unchanged in any case, one can set the first terms in both numerator and denominator on the right of (6) equal to the same constant, k. That is,

$$\alpha s''+\rho_0\doteq\alpha s'+\rho_0\doteq k. \tag{11}$$

One now has for (6)

$$p=(Z_ck+R_s'')/(Z_ck+R_s'). \tag{12}$$

If all primed quantities refer to a copper wire bridge of resistance, R_s', and constructed of the same wire as the parallel wires, it is possible to neglect R_s' compared with Z_ck. Using (8c) and (11) it follows that the following inequality is true.

$$Z_c\alpha s'=rs'/2\leqq kZ_c. \tag{13a}$$

If the length of the bridge, which is equal to the wire separation, is small compared with the distance, s', between the copper wire bridge and the voltmeter when adjusted for resonance, it follows that

$$R_s'\ll Z_ck. \tag{13b}$$

[8] R. King, Proc. I. R. E. **23**, 885, Part IV (1935).
[9] Reference 8, p. 923.

In the case at hand the copper bridge had a length of two centimeters, the distance s' was over 150 cm. One concludes that when R_s' refers to the resistance of a copper wire bridge, one can write (12) as follows.

$$p=1+R_s''/Z_ck. \tag{14}$$

Now let R_s'' be the resistance of a bridge consisting of a piece of Nichrome wire of known diameter and direct current resistance. Using skin effect formulas R'' can be calculated at any desired frequency. For example, a 2-cm length of No. 30 Nichrome wire at a wave-length of 210 cm has a resistance of

$$R_n''=0.63 \text{ ohm}. \tag{15}$$

The radiation resistance of a short length of wire with approximately uniform current distribution is roughly given by the well-known Hertzian formula,

$$R_r=80\pi^2(s/\lambda)^2. \tag{16}$$

For a two-centimeter length at a wave-length of 210 cm one has

$$R_r=0.07 \text{ ohm}. \tag{17}$$

The total effective resistance of the two-centimeter length of Nichrome wire is, therefore, approximately given by

$$R_N''=0.70 \text{ ohm}. \tag{18}$$

The observed ratio of voltmeter deflections for the copper bridge and for the Nichrome bridge (corrected for linear voltmeter scale in each case) was found to have the following value, p_{cN}.

$$p_{cN}=2.25. \tag{19}$$

Using (18) and (19) in (14), one computes Z_ck to have the following value.

$$Z_ck=0.56. \tag{20}$$

The next step in the calculation is to substitute the unknown tank circuit resistance for R'', and determine the deflection ratio of the voltmeter for the copper wire bridge and for the tank circuit bridge. This was found to be,[10]

$$p_{ct}=2.08. \tag{21}$$

[10] It is to be noted that No. 30 Nichrome wire was chosen deliberately because it produced a deflection as near to that of the tank circuit as possible with the choice of wire available. Error in approximations involved in (14) are in this way minimized.

Using (20) and (21) in (14) one readily calculates the desired effective resistance, R_t'', of the tank circuit. It is

$$R_t''=0.60 \text{ ohm}. \tag{22}$$

By using the thermocouple and the condenser as a bridge the resistance of the external part of the tank circuit was measured in the same way. It is

$$R_x''=0.17 \text{ ohm}. \tag{23}$$

The direct-current resistance of the thermocouple alone is 0.14 ohm. Because of the fineness of the resistance wire in the heater of the thermocouple only a small increase in resistance due to skin effect would be expected.

In order to calculate the ultra-high frequency power consumed in the tank circuit or radiated from it, it is necessary to know the ultra-high frequency current flowing in the circuit. Because of the very short length of the circuit used compared with a half-wave-length, one can assume the current amplitude to be sensibly constant and equal to its value in the thermocouple. Although one cannot expect a thermocouple, even when constructed for use at reasonably high frequencies, to give exactly correct readings at ultra-high frequencies, the error is not great for a properly designed unit. The effect of capacitance

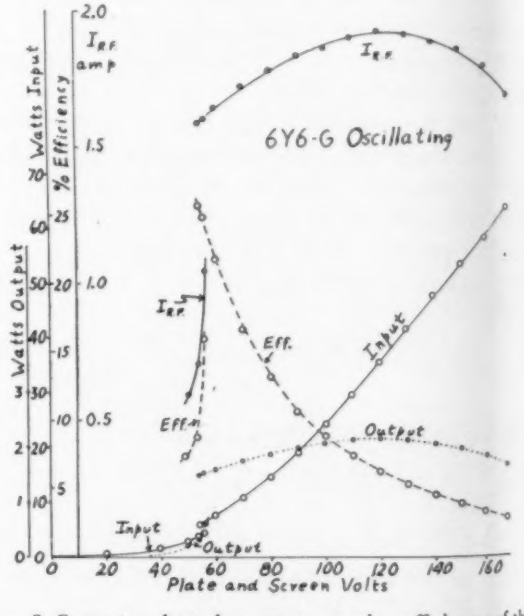


FIG. 8. Output and total power conversion efficiency of the 6Y6-G for the circuit used in Fig. 7.

in parallel is somewhat compensated by radiation, so that a very fair measure of ultra-high frequency current is obtained. Using the thermocouple reading without correction, the power output of the entire tank circuit was computed from the formula, $I_{R.F.}^2 R_t$, and plotted in Fig. 8 together with the high frequency current, $I_{R.F.}$. The power input and the efficiency are also shown. The efficiency in terms of the outside part of the tank circuit only is obtained from the total efficiency by multiplying by the ratio, $R_z/R_t = 0.28$. One may conclude from the total tank circuit efficiency that by reducing the resistance of the circuit within the tube by shortening and thickening the plate and screen leads, efficiencies approaching the total power conversion efficiency of 25 percent may be obtained in the external part at a frequency as high as 150 megacycles. With the 6Y6-G as it is, a maximum efficiency of only seven percent is obtained in terms of the external part of the tank circuit. Even this value compares favorably with values listed by Kelly and Samuel for a standard 75-watt tube.[11] A value of 25 percent is of the order or magnitude obtained by them for a specially designed high frequency tube.

The Suppression of Oscillations in Beam Tube Circuits

After demonstrating that the beam tubes of the types 6Y6-G, 6V6-G and 6L6-G generate ultra-high frequency oscillations in circuits of almost any length, and for almost all ranges of plate, screen and grid voltages, the question arises, how may such oscillations be prevented when the tube is used as an amplifier? It is certainly clear, that the attempt to suppress the high frequency currents by connecting blocking condensers across the socket terminals will have precisely the opposite effect, since the tubes oscillate vigorously at their highest frequencies when only short connections join plate and screen. An alternative method is to use chokes in the plate, screen and grid connections. Although this method is frequently successful in eliminating the oscillations, it is not entirely simple to wind small coils which will suppress them over a very wide band of possible frequencies. A simpler and more effective way is to connect small resistors in the screen and grid circuits only. Experiments show that ultra-high frequency oscillations will not be maintained if a resistance above 10 ohms is inserted in the screen lead at the socket. Due to the small screen current in normal operation, small resistors of even a 100-ohm size may be connected without altering the characteristics in any significant way. For most purposes it is adequate to use a resistor only in the screen lead as suggested, since oscillations are most easily generated in the screen-plate circuit. In some instances it appears that oscillations may occur in the control grid-plate circuit when a resistor is placed only in the screen lead. It is, therefore usually advisable to connect a second small resistor in the control grid lead as well. Since the control grid takes no current when the tube is not oscillating, such a resistance will not affect the tube characteristics.

In conclusion it may be said that beam tubes appear to offer promising possibilities as generators of ultra-high frequencies. By proper design of the screen and plate leads frequencies well over 200 megacycles should be obtained with large output and reasonably high efficiency. Without changes in design the 6Y6-G and the 6V6-G yield a large output at frequencies up to 200 megacycles with efficiencies between five and seven percent in terms of power delivered to the external part of a tank circuit.

[11] Kelly and Samuel, Bell Syst. Tech. J. **14**, 97 (1935).

Some Properties of the Hydrogen Arc

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(Received February 24, 1939)

The gradient E, total voltage e, and current density I in the one-atmosphere hydrogen arc between pure carbon electrodes in the 0–10-ampere range are measured by an oscillographic method. An abrupt change in e takes place at 2 and 0.6 ampere, and in E at 2 amperes, leading to the identification of three states of the hydrogen discharge in this current range and pressure. Rapid motion pictures of this arc at pressures above atmospheric show violent arc movements originating from convection forces. The exponent of the $E-i$ relation is found to be 0.70 for the normal arc state at $p=1$ atmos.

Introduction

SOME observations on the arc in hydrogen have been reported by Mackay and Ferguson,[1] by Langmuir,[2] and, in connection with hydrogen welding, by Weinman and Langmuir,[3] and by Alexander.[4] More recently, water vapor arcs, which show many of the properties of hydrogen arcs, have been studied by Lotz.[5] Hydrogen glow discharges at high pressure have been the subject of recent investigations by Thoma and Heer[6] and by Kiessling.[7]

The instability of the arc in hydrogen at pressures above atmospheric has been noted previously.[8] More careful work with the vibrating electrode chamber confirms this observation. With pure carbon electrodes (and 1500 volts d.c.) it has been impossible to obtain electrical data satisfactory for measurement purposes in the 1–10-ampere range at pressures above atmospheric. In addition to other sources of high pressure instability, very rapid movements of the arc column develop in hydrogen. These movements probably originate in turbulent convection currents in the gas, an effect which increases with pressure. The photographs of Fig. 1 show two frames of a high speed motion picture of an arc in hydrogen at a pressure of 20 atmospheres, showing extremely rapid movements of the arc column. The electrodes are tungsten, anode above, the current 5 amperes, the arc length 12 mm, and the time separation of the two frames is 0.0005 second. Any method of measuring the gradient or arc voltage in the hydrogen column at high pressure will require means for stabilizing these convection currents. At one atmosphere

Fig. 1.

[1] G. M. J. Mackay and C. V. Ferguson, J. Frank. Inst. **181**, 209 (1916).
[2] I. Langmuir, Gen. Elec. Rev. **29**, 153 (1926).
[3] R. A. Weinman and I. Langmuir, Gen. Elec. Rev. **29**, 160 (1926).
[4] P. Alexander, Gen. Elec. Rev. **29**, 169 (1926).
[5] A. Lotz, Zeits. f. tech. Physik **15**, 187 (1934).
[6] H. Thoma and L. Heer, Zeits. f. tech. Physik **14**, 385 (1933).
[7] E. Kiessling, Zeits. f. Physik **96**, 365 (1935).
[8] C. G. Suits, J. App. Phys. **10**, 203 (1939).

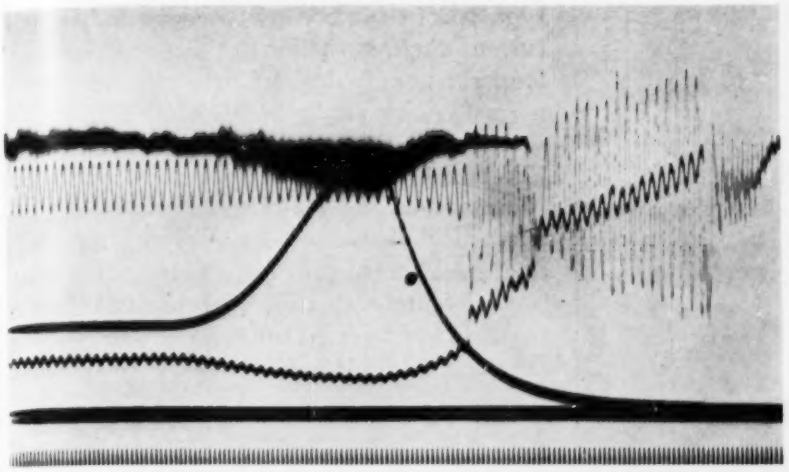

FIG. 2.

pressure, however, the hydrogen arc (with a thermionic cathode) has satisfactory stability, and a great many records similar to Fig. 2 have been obtained.

EXPERIMENTAL METHOD

For the purpose of measuring the gradient E (volts cm^{-2}) and current density I (amp. cm^{-2}) in the positive column of the hydrogen arc, use is made of the oscillographic method which employs the vibrating electrode chamber previously described.[9] For details of this method the reader is referred to the earlier publication, but it can be stated briefly that the gradient measurement is made by recording the amplitude of the voltage change which takes place when one electrode is vibrated rapidly through a small amplitude along the axis of the arc. The current density I is measured as

$$I=\frac{i}{0.785D^2},$$

where i is the arc current and D is the photographically recorded arc diameter. The quantity I is an average value for the cross section of the arc. The total arc voltage e is also recorded. E, e, and D are thus measured on the same oscillographic record as a function of arc current which varies slowly from 10 amperes to zero. An oscillogram of this kind is shown in Fig. 2.

In the present instance the arc burns vertically at a mean electrode separation of 5 mm. The electrodes are $\frac{1}{4}''$ diameter (National Carbon) spectrographic carbons. At this length the hydrogen arc has attained a diameter and gradient which are constant with respect to further increases in length; the reported measurements of E and I thus apply to the positive column of the hydrogen arc at a pressure of one atmosphere absolute.

A new effect which appears without exception on

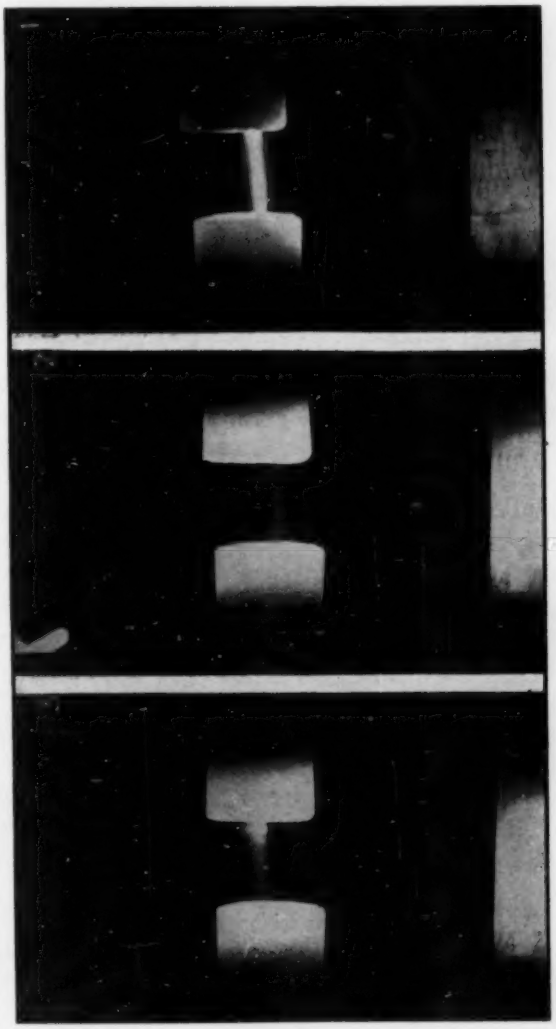

FIG. 3.

[9] C. C. Suits, Phys. Rev. **55**, 561 (1939).

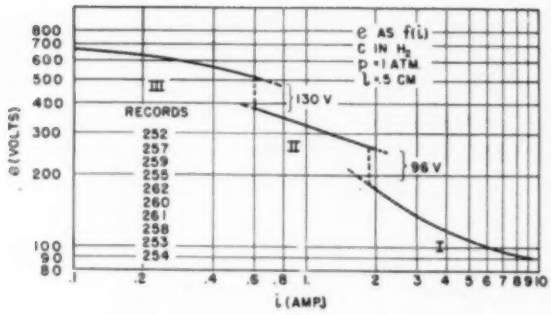

FIG. 4.

the records is the transition to multiple "glow" states at low current,[10] shown in the record of Fig. 2. One observes a lowest voltage state, *I*, which might be called the normal arc, in the current range above 2 amperes. This type of discharge is the hydrogen arc known to the literature and is shown in the photograph of Fig. 3–1. In the current range 2–6 amperes a discharge, *II*, appears, which may be called tentatively a glow because of similarity to the low pressure glow discharge. This glow state *II* is a striated discharge (evident in original photographs, probably not in reproduction) and has a prominent cathode dark space, as shown by Fig. 3–2. In the range 0.6–0.1 ampere a discharge, *III*, develops, as shown by Figs. 2 and 3–3. This glow state *III* has a column similar to *II*, but the cathode dark space is now occupied by an intense glow from which a number of streamers emanate. From a set of 10 oscillograms the e–i and E–i curves of Figs. 4 and 5 have been plotted. It appears that the transition from *I* to *II* at $i=2$ amperes is accompanied by a change in gradient of 250 volts and a change in total arc voltage of 96 volts (depending to some extent on the current), while the transition from *II* to *III* involves no change in gradient but a change in arc voltage of approximately 130. When the information given by the photographs is considered, it seems evident that this 130 volt change between *II* and *III* occurs at the cathode. It appears, therefore, that in addition to a normal arc state *I* and a glow state there is a still further type of discharge *III*.

Incomplete data on tungsten electrodes in hydrogen suggest the presence of 4 discharge types; 3 of these occupy positions on a voltage-current diagram similar to those reported above for carbon electrodes. A fourth type lies near the normal arc and may be identical with the low voltage transition shown by Mackay and Ferguson.[1]

Further incomplete observations point to the possibility of four discharge types for copper electrodes in nitrogen. Two discharge types have been definitely identified for Cu and Ag electrodes in hydrogen. When brass or zinc electrodes are used in hydrogen, we have been able to obtain only the arc state.

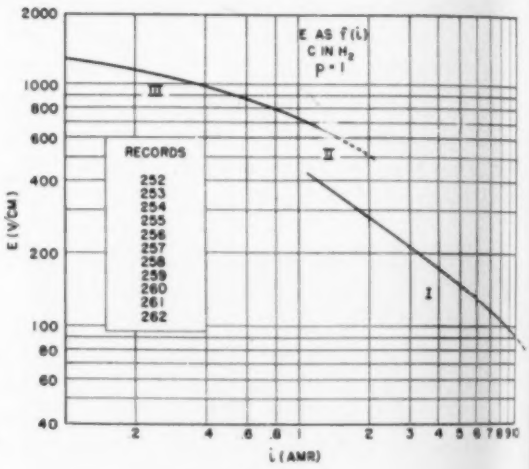

FIG. 5.

An interpretation of these multiple states must await more comprehensive measurements. There is good evidence that in the case of carbon and tungsten electrodes the lowest voltage state *I* is obtained when the cathode is hot enough for thermionic emission, and one of the glow states when it is not sufficiently hot. The striated discharge *II* may be analogous to the low pressure glow discharge with positive ion bombardment of the cathode as the source of electrons. If these two possibilities are used up, very little in the way of a cathode mechanism is left for the type *III* discharge. The changes in arc voltage between *I* and *II* and between *II* and *III* are too large to be identified with any of the critical potentials that are available.

For the normal arc state *I* in hydrogen we find that

$$E=500i^{.70}.$$

[10] C. G. Suits, Phys. Rev. **53**, 609 (1938).

The Rate of Plastic Deformation in Lead Under Compression

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(Received February 25, 1939)

It is shown that the velocities of plastic deformation, deduced from previous experimental data on lead cylinders, are in satisfactory accord with the relation

$$v = a \exp(bP),$$

where a and b are constants, and P is the prevailing pressure. Integration of this equation leads to the following expression for deformation as a time-function:

$$\epsilon = 1 + (1/bP_0) \ln (abP_0 t + C),$$

where P_0 is initial pressure and C is a constant of integration. Means for evaluating C are given. This equation, requiring adjustments in only a, is found to represent very well the observed relations between deformation and compression-time for four different initial pressures. It is concluded that plastic deformation in lead is governed principally by the exponential law for velocity.

Introduction

In a previous experimental report[1] on the plastic deformation of lead cylinders under static compression, curves were submitted showing deformation as a function of the time of application of various loads. Also shown were hypothetical curves, linear in character, in approximate accord with the data. Examination of the latter curves indicates that the velocity of deformation is approximately constant for constant pressure, and that the variations in each are concomitant. This conclusion is in accord with numerous other "long-time" tests made on iron and other metals, where the deformation velocities are small.[2] Further mathematical treatment has been undertaken to verify the indicated pressure-velocity relation, and establish an analytical expression for it.

Discussion

The original experimental curves being of the form

$$\epsilon = \phi(t), \tag{1}$$

where ϵ = deformation, t = time in minutes, the velocity of deformation, $v = d\epsilon/dt$, is obtained as the slope of the curve representing Eq. (1). The slopes of the curves for three different, constant loads have been measured at appropriate intervals, and corresponding instantaneous pressures, P, have been calculated from the relation

$$P = (1 - \epsilon)P_0. \tag{2}$$

The initial pressure, $P_0 = F/A_0$, where F = load, and A_0 = initial cross section of the test cylinder. The results are plotted in Fig. 1, along with points obtained from the hypothetical curves mentioned above.

The distribution of points is in accord with the well-known fact that yield-stresses (or required pressures) are great at high velocities of deformation. However, the relation evidently is not a simple linear one over a large range of deformations. Results obtained by Cassebaum[3] in some tensile tests on soft iron, suggested the application to the present data of the relation

$$v = a \exp(bP), \tag{3}$$

where a and b are constants. The curve of this equation, for which the values $a = 1.338 \times 10^{-7}$ and $b = 0.07863$ have been assigned, is drawn in Fig. 1. While representing all the data fairly well, it practically coincides with that for an initial pressure of 183.2 kg/cm².

That the good agreement of Eq. (3) with observation in this case is not due to fortuitous measurements of slope at a few points, is indicated by the following considerations. Combining Eqs. (2) and (3), we obtain

$$v = d\epsilon/dt = a \exp[b(1 - \epsilon)P_0]. \tag{4}$$

[1] W. J. Lyons, J. App. Phys. **9**, 641 (1938).
[2] A. Nadai, *Plasticity* (McGraw-Hill, 1931), pp. 21 and 273.
[3] H. Cassebaum, Ann. d. Physik **34**, 106 (1911).

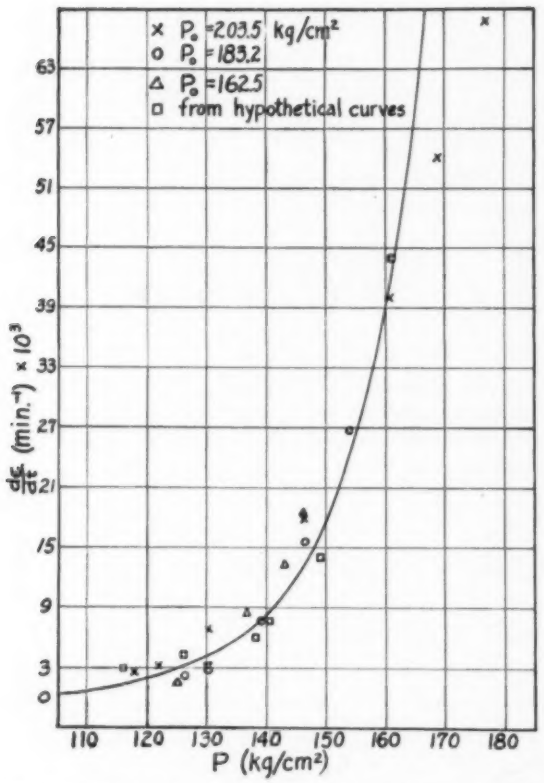

FIG. 1. Observed velocities of deformation as functions of prevailing pressures. Curve is for Eq. (3), with $a=1.338\times10^{-7}$ and $b=0.07863$.

On transposing appropriate terms and integrating, this equation becomes

$$\epsilon=1+\frac{1}{bP_0}\ln(abP_0t+C), \tag{5}$$

where C is a constant of integration. The right-hand side of this equation gives the explicit form of the function $\phi(t)$ in Eq. (1). On substituting in Eq. (5) the above values of a and b, and $P_0=183.2$, $C=0$, we obtain finally

$$\epsilon=0.086+0.160\log t. \tag{6}$$

This curve is plotted in Fig. 2, along with experimental points for $P_0=183.2$ kg/cm².

Equation (5) may be written in the form,

$$\epsilon=1+\frac{1}{bP_0}\ln(abP_0)+\frac{1}{bP_0}\ln(t+C'), \tag{7}$$

where $C'=C/abP_0$. The other curves given in Fig. 2 are obtained from Eq. (7) when a is given the values in Table I. The following relation for C' was established empirically:

$$C'\equiv C/abP_0=0.098(183-P_0). \tag{8}$$

The second and third members of this equation are both decreasing functions of P_0. Their approximate equality may be formally established by a series expansion of C/abP_0, with the arbitrary assignment of a fitting value to C. More realistically, however, Eq. (8) amounts to a means for evaluating the constant of integration C. The simple expedient of placing $\epsilon=0$, at $t=0$, in Eq. (5), to evaluate C, cannot be employed, since it appears that the equation is not valid in the neighborhood of $t=0$. Evidently the value of C changes with P_0.

No simple change in the form of the term containing a, namely $(1/bP_0)\ln(abP_0)$, has been found, to permit use of a single value for a in an equation applicable to all four initial pressures.

CONCLUSION

The present analysis strongly supports the conclusion that the rate of deformation of lead

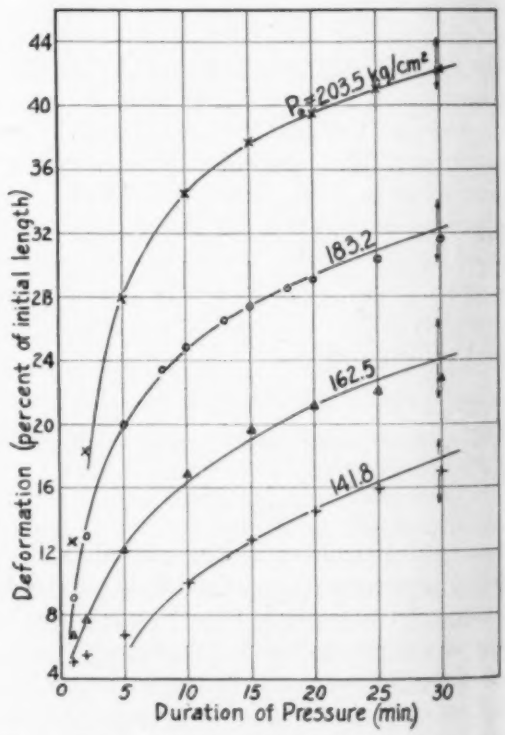

FIG. 2. Theoretical curves based on Eq. (7) and Table I. It should be noted that all experimental points are means of sets of five individual observations, the extreme variation in which, at 30 min., is indicated by arrows.

TABLE I. *Numerical values of a.*

P_0 (KG/CM²)	a $\times 10^7$
141.8	2.751
162.5	1.482
183.2	1.338
203.5	2.175

under static compression is governed fundamentally by Eq. (3), after the initial, adjustment stage in the deformation has been passed. It is significant that the constant b is applicable to all four deformation-time curves, and that the different values of a lie in a small range. While the values 1.482×10^{-7} and 2.245×10^{-7} cannot be used in Eq. (3) for a to obtain curves in close agreement with any set of experimental points in Fig. 1, a fairly satisfactory fit is obtained when other values of b, not differing greatly from 0.07863, are used at the same time. The positions of the curves in Fig. 2 are very critical, in the ϵ-direction, to small changes in the term $(1/bP_0)\times\ln(abP_0)$. It is reasonable to assume, then, that minor factors affecting this term may cause sensible discrepancies between basic theory and experiment.

One of these factors is probably the slight bowing-out, into a barrel shape, of the cylinders under compression. This effect tends to give larger actual values to P over planes near the bases of the cylinders, than are calculated by Eq. (2). Over the central planes the actual pressures are less than the calculated. At the larger deformations this error is likely to be greatest. To get equivalent slopes on the different, experimental deformation-time curves, one must go to larger deformations under the greater loads than under the smaller. For equal velocities, therefore, the calculated pressures will be too small for those points associated with greater loads. This conclusion is fairly well borne out by the dispersion of the points in the lower region of Fig. 1.

There is also the consideration that the law expressed by Eq. (3) may itself be invalid at the higher velocities encountered during the initial stages of deformation. It is reasonable to suppose that a different displacement of each deformation curve at later times will result. This effect is reflected in the need for a different C for each P_0. Without a knowledge of the law relating deformation and time in the initial stage, the direction or magnitude of this displacement cannot be predicted.

At low deformation pressures it appears that the logarithmic relation between deformation and time degenerates into a practically linear one. These cases have not been treated in the present analysis.

Note added in proof.—In a recent article, Nadai[4] gives, as most compatible with observations in creep tests on metals, the relation

$$v=v_1\sinh\sigma/\sigma_1 \qquad (9)$$

where σ=stress, and v_1 and σ_1 are constants. Applying the present writer's data for lead and placing $v_1=2a$, and $\sigma_1=1/b$, velocities have been computed according to Eq. (9). The differences between velocities thus obtained, and those given by Eq. (3) are vanishingly small. With the values which the constants a and b have for lead, the second term of the hyperbolic sine function, namely $a\exp(-bP)$, is practically zero. Thus, while the data of Fig. 1 extends the validity of Eq. (9) to apply to static *compression* in lead, the simpler, exponential function adequately describes the deformation, and is more manageable mathematically.

More recently, Tyte[5] has announced the completion of tensile tests on lead, in which he found Eq. (3) to hold for viscous flow at any given temperature. Experimenting at various temperatures between $-180°$ and 162°C, he obtained the general formula

$$v=\delta\exp(\beta PT-\alpha P+\gamma T), \qquad (10)$$

where T=absolute temperature, and α, β, γ and δ are constants. At constant temperature, Eq. (10) reduces to Eq. (3).

[4] *Stephen Timoshenko Anniversary Volume* (Macmillan, 1938), p. 155.
[5] L. C. Tyte, Proc. Phys. Soc. **51**, 203 (1939).

The Lack of "Sucking" Action by the Cathode Blast of Mercury Vapor in a Pool Rectifier

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(Received March 1, 1939)

In the all-glass mercury arc rectifier Hg vapor streams from the cathode pool past the side arms into the condensing dome. Experiments of von Engel and Steenbeck offer indirect evidence that this blast of vapor reduces the mercury vapor pressure in the side arms to as little as $\frac{1}{10}$ of that in the dome. Direct measurements of vapor pressure have been made using ionization gauges on a side arm and on the condensing dome and using thermocouples on the rectifier wall at the condensation edge and on the dome. Both free and anchored cathode spots were used. No trace of "sucking" action was found. The theory of the Bernoulli Effect applied to this case gives a maximum possible reduction of pressure below that in the dome of 50 percent.

I. INTRODUCTION

IN the all-glass mercury arc rectifiers with pool cathode a blast of mercury vapor originating at the cathode surface streams past the side arms containing the anodes and possibly grids and flows with expanding cross section into the condensation dome from which the liquid mercury drops back into the cathode pool.

Experimental results of von Engel and Steenbeck[1] indicate a "sucking" action exerted by the streaming vapor upon the vapor in the side arms. Above a range of low arc currents they found that the mobility of the electrons in the side arms was far higher than corresponded to the saturated vapor pressure at the temperature of the condensation edge on the dome even when they corrected for the maximum possible excess temperature of the gas at the axis of the side arm. Their results, expressed as apparent pressure in the side arm as ordinate against the saturated pressure of mercury vapor at the condensation edge in the dome of the tube as abscissa, are shown by the dotted curve in Figs. 1 and 2. With increasing arc current, not indicated on the curves, these two pressures at first maintain equality, but as the dome pressure (abscissa) increases past seven microns the calculated side arm pressure (ordinate) passes through a maximum at a little less than eight microns, falling to as low as five when the dome pressure reaches 100.

As a check on the idea that this phenomenon was due to an actual evacuation of the side arm by the action of the main mercury vapor stream flowing up into the dome, these experimenters added a small amount of argon and later other gases[2] to a rectifier and measured the distribution of its partial pressure with McLeod gauges when the tube was in operation. The results corresponded qualitatively with the apparent pressures for mercury alone.

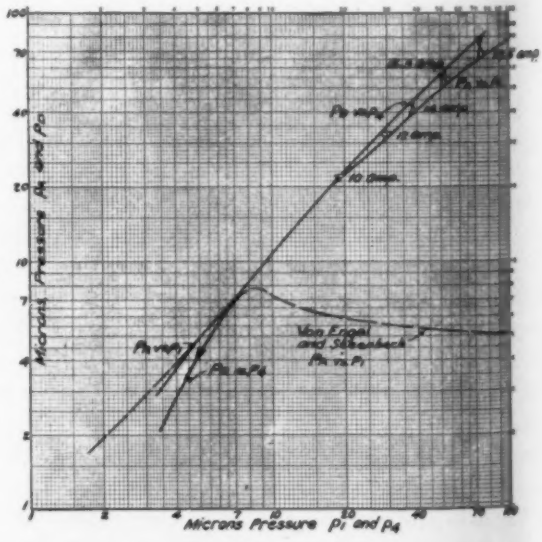

FIG. 1. Mercury-rectifier vapor pressures at various arc currents with free cathode spot. Curve p_A *vs.* p_1 is side arm *vs.* condensation edge pressure, solid curve experimental, dashed curve according to von Engel and Steenbeck. Curve p_D *vs.* p_4 is ionization gauge *vs.* thermocouple pressure at dome top.

[1] A. v. Engel and M. Steenbeck, Wissen. Veroffent. a. d. Siemens Werken, **15**(3), 42 (1936); Physik. Zeits. **37**, 830 (1936).

[2] A. v. Engel and M. Steenbeck, Zeits. f. tech. Physik **18**, 491 (1937).

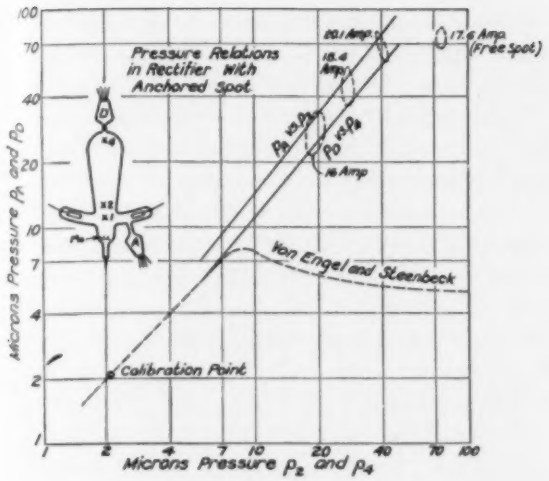
Pressure Relations in Rectifier With Anchored Spot
Von Engel and Steenbeck
Calibration Point
Microns Pressure p_2 and p_4
Microns Pressure p_4 and p_0

FIG. 2. Similar to Fig. 1 with anchored cathode spot. Here p_2 is condensation edge pressure.

It should, perhaps, be remarked that this confirmatory test with argon is really no test of the self-sucking action of mercury vapor. Once an argon atom has diffused from the side arm into the rapidly flowing stream of mercury vapor which drives it toward the upper portion of the condensation dome, it has little probability of diffusing back through the on-coming rush of mercury atoms so that one might reasonably expect the result found for argon. Where mercury alone is concerned, however, there is a constant fresh supply of mercury atoms to the side arm from the passing stream of mercury vapor itself. How much sucking is theoretically possible is treated at the end of this article.

The experimental results have been questioned by Klarfeld[3] from several angles, none of which bear on the presence of the so-called "sucking" action under the special arc conditions which existed in the von Engel and Steenbeck tests.

The technical importance of the "sucking" phenomenon as well as its unorthodoxy made a more direct test desirable, which is described in the present paper.

II. APPARATUS

The present experiments were designed to make this direct test on the mercury vapor pressures in side arms and dome through the use of ionization gauges. The rectifier which was used is shown semi-schematically in Fig. 2. The capacity of the dome was approximately 2.2 liters. Each of the two side arms was 5 cm in diameter. At the side arms the main tube had a diameter of 7.7 cm and this increased to a maximum diameter of 11 cm, 25.5 cm higher. Ionization gauge IG_A branched off at right angles from anode arm A and IG_D extended axially from the dome of the main tube. These gauges contained UX210 plates and grids and V filaments of 4-mil tungsten and 4 cm lighted length.

Any mercury condensing in these gauges or in the tubing connecting them to the rectifier would be a source of error. This tubing was therefore kept hot with a winding of resistance wire and the gauges were enclosed in ovens. The temperatures maintained were roughly 100–120°C which exceeded the temperature of saturation of any pressure encountered during the experiments. The uncertainty introduced into the measurements by the existence of temperature differences were smaller than the errors for which other factors were responsible and for the elimination of which an unwarrantedly complicated set-up would have been required considering the purpose of the tests.

To avoid long time pressure readjustments enough heat insulation at the anode arm extremities was used to prevent condensation of mercury there.

For the purpose of further pressure comparisons in the rectifier, thermocouples were attached to the tube walls by means of putty and plaster of Paris. In doing this care was observed to use as little of the adhesive material as possible consistent with good thermal contact between the couple and the glass, since a change in temperature caused by the presence of the temperature-measuring device itself was undesirable. The fact that there was no change in shape of the condensation edge in the neighborhood of a thermocouple indicated that this was achieved.

Thermocouple No. 1 lay at the condensation edge for the free cathode spot test, No. 2 at the edge for the anchored spot test, and No. 4 on the dome roof. Early in the tests it was found that the temperature variation across the condensation edge was negligible so that a lack of

[3] B. Klarfeld, Physik. Zeits. Sowjetunion **11**, 669 (1937).

exact coincidence between couple and edge was unimportant.

The usual procedures for degassing metallic parts of the ionization gauges and the graphite electrodes of the rectifier were used, and the glass was torched for the same purpose.

III. Use of Ionization Gauge at Higher Hg Vapor Pressures

The use of an ionization gauge at pressures of mercury vapor in the range here necessary, roughly up to 100 microns, is not common; and it was therefore necessary to make sure that gauge readings could be interpreted at these comparatively high pressures. For this purpose an evacuated tube containing mercury, which had already been prepared by Dr. Overton Luhr in this laboratory, and which was already mounted in an electric oven for controlling the temperature, was used. By using approximately the same electron current and voltages that he did, I was able to check his results roughly, but I found that low grid voltage and low electron current had two advantages. First, the gauge readings remained linear with pressure to higher pressures, and second, when deviations from linearity finally occurred they were smaller. With 17 v on the grid, −4.5 on the plate, both measured with respect to the negative end of the filament, and 0.1 milliamp. of grid current the ion current was proportional to pressure up to 30 microns. At 70 microns it showed a drop of only ten percent below the linearly extrapolated value. Since the gauges attached to my experimental tube had the same construction as Luhr's (except that Luhr's tube had a 3-mil filament which should not affect the characteristic appreciably), I assumed that their characteristics would be similar to the characteristic of his tube as regards deviation from linearity.

IV. Experimental: Free Cathode Spot

Ionization gauge readings were started at room temperature with no current through the rectifier, and these were used to establish the calibration of the ionization gauges. At each successive value of current the rectifier was allowed to run for about 5 min. in order to reach a constant temperature condition and then the thermocouple temperatures and ionization currents were read. Five minutes later another set of readings was taken as a check on the first.

The cathode spot was free in the first tests, and the splashing of mercury droplets through the rectifier and into the anode arms was quite evident. Undoubtedly some of these droplets, which were 0.2 mm in diameter and less, fell down into IG_A and were responsible for the rather wide fluctuations in the ionization current through that gauge. Under these circumstances the minimum value of the ionization current would most nearly correspond to the actual vapor pressure of the mercury vapor in the side arm so that it was this reading which was recorded.

Only at the lower currents through the tube did the temperatures recorded by the thermocouples at the condensation edge exceed the temperature at the dome appreciably; at the higher currents the equality of these temperatures indicated a rather exact equalization of pressure throughout the whole condensing region.

V. Evaluation of Data and Results for Free Spot

The thermocouple reading at the condensation edge, which was that of thermocouple No. 1, and that on the roof of the dome, which was that of thermocouple No. 4, were interpreted in terms of saturated mercury vapor pressure, and the ionization gauge readings were interpreted in terms of mercury vapor pressure. Two curves were then plotted for a single complete set of measurements. The first was the pressure p_A from IG_A against the pressure p_1 from thermocouple 1 (which lay slightly above the level of the center line of the side arm), the second the pressure p_D from IG_D against p_4 from thermocouple 4.

These curves are shown as solid lines in Fig. 1. One reasonably expects p_D and p_4 to be equal throughout the range of measurements. Actually, the gauge indicates slightly higher pressures than the thermocouple, except in the low range where only the lower part of the dome is fully effective in condensing vapor. Under the experimental conditions no significance attaches to this apparent difference. The crucial curve is the other one of the pair, that which gives side arm pressure p_A against condensation edge pres-

sure p_1. Here again p_A does not pursue exact equality with p_1, but it shows no tendency to behave like the von Engel-Steenbeck curve even at ten times the dome pressure which produced their maximum side arm pressure.

The short lines crossing from one curve to the other connect simultaneous observations, and these are labeled with the corresponding arc current.

VI. Anchored Cathode Spot

The possibility remains that by anchoring the spot as von Engel and Steenbeck had done the conditions in the vapor stream would be so altered that the sucking effect would appear. Accordingly, the cathode was modified by the introduction of a ring of sheet molybdenum as indicated in Fig. 2 and the tests were repeated with the changed tube.

It was immediately noted that the condensation edge (which remained constant in position over the whole range of currents used in the tube) lay some 4.5 cm above its former position.

The measurements with the anchored spot were carried out in the same way as those with the free spot. The ionization current in IG_A showed only minor fluctuations, testifying to the steadier conditions or the absence of spray entering the ionization gauge in this case. The results of the series of measurements with the anchored spot are shown in Fig. 2. Here the pressure p_A in IG_A is plotted against p_2 indicated by thermocouple 2.

In this figure the gauge pressures are seen to be consistently higher than the thermocouple pressures, and this is more marked with respect to the side arm and condensation edge than for the dome top measurements. This may be connected with the more regular streaming of vapor from the anchored spot, the momentum of the mass motion adding to the effective pressure in the direction of flow over what is observed perpendicular to the flow by thermocouple 2. We should have to suppose first that a component of the flow was directed toward the side arms resulting in sufficient back pressure there to redirect the stream up the tube, and second, that at the level of thermocouple 2 such a component had vanished.

Whatever the cause of this pressure difference may be, the significant feature of the p_A *vs.* p_2 curve is again the absence of any downward turning suggestive of "sucking action."

VII. Comparison of Free and Anchored Cathode Spots

A comparison of the pressures observed in the rectifier at the same values of current in the two cases of free and anchored spot, respectively, shows that in the latter case these pressures are only $\frac{1}{3}$ to $\frac{1}{2}$ of what they are in the former. See, for instance, the 17.6-amp. free spot observations plotted in Fig. 2. This points to a larger flow of vapor with the free spot. Such an effect is undoubtedly due to the evaporation of the spray droplets which fall on the hot tube walls in that case.

VIII. Comparison of Present Results with Those of von Engel and Steenbeck

The comparison with the von Engel and Steenbeck results is not exact because of the difference in the tube size as well as an undoubted difference in structure. Incidentally those authors have shown no picture of their tube by which any idea could be obtained of the shape of the main body of their tube. It is thought, however, that the absence in the present test of any indication of the kind of effect which their results lead us to expect makes certain the conclusion that no sucking action of the magnitude which they find actually exists.

It is possible that the two sets of results are reconcilable, for von Engel and Steenbeck measured an effective electron mean free path over the cross section of the arm, whereas the present tests give the pressure at the wall. It is to be expected that when the current density is considerable the outward motion of the ions toward the wall will cause a transverse gradient in the gas pressure such that the gas at the axis is rarefied relative to that at the wall.[4] Under these conditions the effective electron mean free path for current conduction over the cross section as a whole would be less than that corresponding to the pressure at the tube walls. There are two

[4] L. Tonks, Trans. Electrochem. Soc. **72**, 185 (1937). See page 196.

difficulties to this explanation, however. One is that the increase in effective mean free path should be as great as must be concluded, namely some 16 times that calculated from the wall pressure; and second, that the effect should become pronounced at such low current densities as were employed in the experiment.

IX. Calculation of Bernoulli Effect in Rectifier

It is the principle of the Bernoulli Effect which must govern any reduction of pressure in the side arms when only Hg vapor is present.

If a gas flows through a tube from a region of higher to lower velocity, whether the decrease in velocity be caused by an increase in cross section or a drop in temperature, the pressure increases. In the rectifier tube both causes operate to slow down the flow velocity. Thus it would appear theoretically possible to have a lower pressure in an anode arm (opposite a high velocity flow point in the main tube) than that at the condensation edge.

The theoretical relation governing the density, volume and pressure of a fixed quantity of the gas as it moves from location (1) to location (2) is

$$(\tfrac{1}{2})\rho_1 v_1^2-(\tfrac{1}{2})\rho_2 v_2^2=p_2-p_1. \qquad (1)$$

Introducing the atom density n, the atom mass m, the absolute temperature T, the cross section area A, and the constant flow rate in atoms per second q, we have the additional relations

$$\rho=nm, \quad p=nkT, \quad q=nvA. \quad (2), (3), (4)$$

With these ρ, n, and v can be eliminated from (1) giving

$$p_2-p_1=\frac{mq^2k}{2}\left[\frac{T_1}{A_1^2}p_1^{-1}-\frac{T_2}{A_2^2}p_2^{-1}\right]. \qquad (5)$$

Taking cross section 1 to be at the higher velocity, higher temperature, smaller cross section position (i.e., at the side arms) and cross section 2 to be at the place condensation begins,

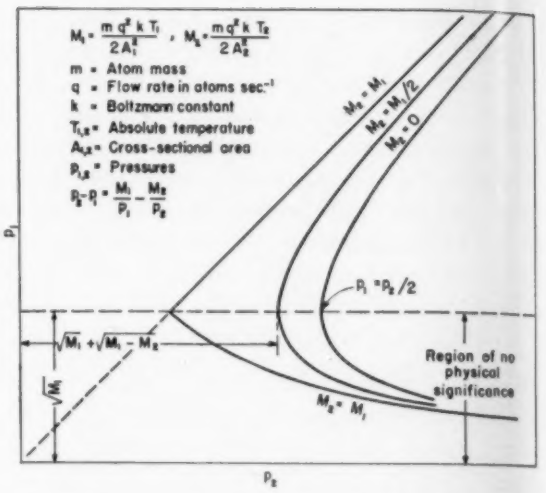

FIG. 3. Theoretical pressure relations in gas flowing with increasing cross section and decreasing temperature. Small cross section high temperature pressure is p_1, large cross section low temperature pressure is p_2.

we see that $T_1A_1^{-2}>T_2A_3^{-2}$. We put M_1 for the whole coefficient of p_1^{-1} in (5), similarly for M_2 and p_2^{-1}. Then

$$p_2-p_1=M_1/p_1-M_2/p_2, \quad M_1>M_2.$$

Without going into algebraic details, it can be stated that the relations between p_2 and p_1 are those shown in Fig. 3. Only the upper branch represents a continuous transition from p_1 to p_2 and hence real conditions, because as M_2 approaches M_1 it is only for the upper branch that p_2 approaches p_1. The maximum ratio between p_1 and p_2 occurs at $p_2=M_1^{\frac{1}{2}}+(M_1-M_2)^{\frac{1}{2}}$ at which point on the curve

$$p_2>p_1\geqq p_2/2.$$

Thus the maximum reduction in pressure is only 50 percent and that corresponds to $T_2/A_2^2=0$, so that the theoretical conclusion is against finding the desired "sucking" action.

Another factor enters to make even the small effect which has just been calculated uncertain, and that is the possible development of a boundary layer in the expanding cross section of the dome.

Photographs of Unusual Discharges Occurring During Thunderstorms

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(Received March 6, 1939)

The known photographs of an unusual type of discharge occurring in intense thunderstorm fields principally near ground objects are described and discussed. A possible explanation of the discharges is suggested.

Introduction

In February, 1938, the authors,[1] in collaboration with Professor Snoddy, described photographs of an unusual electrical discharge obtained with rotating drum cameras. Since this time, six other still photographs of discharges which showed similar characteristics have been studied. Three of these were taken by W. E. Burk, Jr., who cooperated with the authors in attempts to obtain photographs similar to the one previously described near the place where the first was secured. One each of the remaining three photographs were taken by B. W. Cartwright,[2] Alexander Larsen,[3] and R. J. Spickerman.[3] These photographs are collected here for the purpose of comparison and for the benefit of those who may be interested in further study of the type of discharge illustrated.

[1] Holzer, Workman and Snoddy, J. App. Phys. **9**, 134 (1938).
[2] Life, August 23, 1937.
[3] C. G. Abbot, Smithsonian Miscellaneous Collections 92, No. 12 (1934).

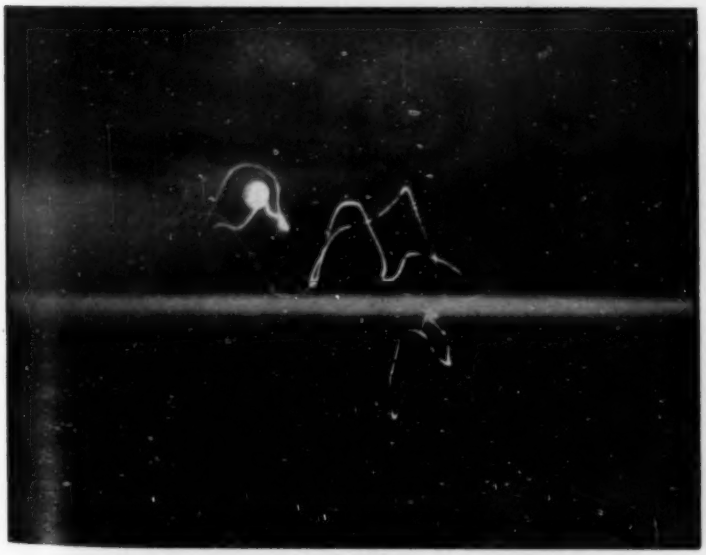

Fig. 1a.

Description of Photographs

Figures 1a and 1b are reproductions[1] of the only moving film camera photographs of a discharge of the type here described that have come to the attention of the authors. They were taken at Santa Fe, New Mexico (elevation 7000 feet) on the night of September 3, 1936. The cameras were mounted rigidly on a bench in a portable laboratory. The discharge was probably about 100 feet from the cameras, although the exact distance is not known since no thunder associated with this flash could be distinguished from the general background of thunder. The discharge occurred within less than one-thousandth of a second after an intense cloud ground stroke not shown on this portion of the film. Analysis of the photographs indicates that the discharge consisted of at least four luminous darts moving with a projected velocity of the order of 10^7 cm/sec. The most notable features of this discharge are: (1) its irregularity of path and rapid reversals in direction, (2) its proximity to ground objects with no apparent contact with the ground, (3) the beaded nature of the path, and (4) the progress of the discharge in two directions from a single point.

Figures 2, 3 and 4 are reproductions of photographs obtained by W. E. Burk, Jr., during September, 1937 at Santa Fe within a quarter of a mile of the place where the first discharge was photographed. The photographs in Figs. 2 and 4 were obtained with a Rolleiflex camera and

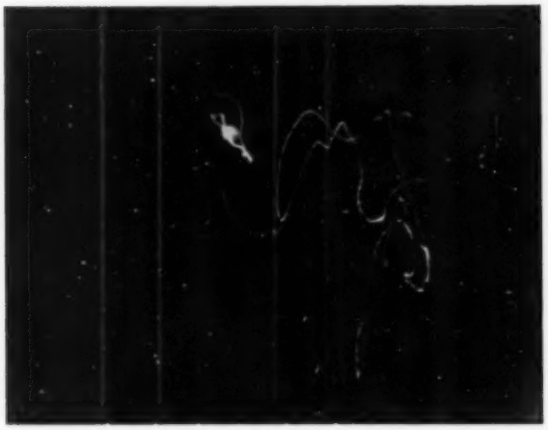

FIG. 1b.

that in Fig. 3, with an Argus. In each case the camera was held in the hand of the photographer. That the camera was not moved appreciably in any case is clearly shown by unblurred ground objects illuminated by the discharges. In each of the photographs, objects in the background were illuminated by nearly simultaneous lightning discharges of the usual type. None of these lightning strokes happens to lie within the field of the camera.

In Fig. 2, the discharge was within 15 feet of the camera and close to the limbs of a willow tree. The very bright portion of the discharge is due to the extremely tortuous path of the stroke. The diameter of the path is approximately the same in this region as it is elsewhere. The lacy illumination in the background is probably a discharge from the sharp points of the tree.

FIG. 2.

In Fig. 3, the discharge is less than 50 feet from the camera. The conducting path passes in front of the nearer pole at left center.

In Fig. 4, the discharge is less than 100 feet and probably about 30 feet from the camera. Because of the markedly different background illumination offered by the ground and the sky, it was necessary to mask the sky during part of the printing exposure in order to show all of the stroke details on a single print. The sharp horizontal line below the middle of the picture is very close to the true horizon. The very sharp apparent contrast between sky and ground is due to the masking. A line of trees 100 feet away may be seen silhouetted against the sky.

The last three photographs were obtained under intense storm conditions, and no thunder which could be associated definitely with these discharges was heard.

Figure 5 is the reproduction of the Cartwright photograph taken during a severe electrical

FIG. 3.

storm on July 21, 1937 at Deer Lodge, Manitoba. The camera was resting on a porch ledge 37 feet from the caragana hedge along which the discharge traveled. The shutter was held open by a cable release for some 15 minutes before the discharge occurred. Cartwright described the glare as blinding. Since the foreground objects, especially the hedge, illuminated by the discharge are not blurred, the camera was apparently not in motion at the time of the discharge. The illumination of the background objects, however, is clearly due to other lightning flashes.

This discharge is similar to the Santa Fe

FIG. 4.

photographs with respect to type of path, proximity to ground objects, and apparent failure to strike ground objects. It differs in that the path appears to be broader and ribbon-like, or possibly tubular, in structure.

Figure 6 is a reproduction of the photograph obtained by A. Larsen near Chicago on the night of May 21, 1908 and published by Dr. C. G. Abbot in 1934. The photograph was obtained with a camera rotating one revolution in five seconds. Due to the very low speed of rotation, the camera could not be expected to produce appreciable distortion in a fast single stroke. The angle of elevation of Larsen's camera was 15°. He estimates the thunder time to be less than one second and takes 1000 feet as a reasonable distance. On this assumption, he points out that the stroke diameter is 18 feet. The photograph bears some resemblance to the Cartwright photograph except for the large disparity in estimated diameter of the discharge, and in apparent distance above ground.

Figure 7, a reproduction of the photograph by Spickerman taken on July 17, 1908, was published with the preceding photograph. Spickerman estimated the flash to be one-half mile above the ground and approximately 10,000 feet from the camera. The camera, held on the observer's lap, was intended to be stationary. In Larsen's original discussion, he points out that the camera must have been in motion. Larsen observed four separate rushes, while Abbot believed that he could identify six. The photograph may very well represent a lightning discharge of the type under discussion, but the conditions under which the photograph was taken make it difficult to draw any definite conclusions.

SUMMARY OF OBSERVATIONS

The various discharges described above have a number of characteristics in common:

(1) Nos. 1, 2, 3, 4 and 5 certainly occurred within a few feet of ground objects as indicated by the illuminated background objects. The distances of Nos. 6 and 7 above ground are uncertain. Larsen's and Spickerman's estimates of flash distance lead to the figures 250 feet and 2500 feet, respectively, above ground. However, it should be remembered that it is very difficult to associate thunder with a particular flash when the flashes are frequent and thunder almost continuous. If there were little sound associated with the above flashes, the distance might be assumed, erroneously, to be the same distance as a more intense and nearly simultaneous flash.

(2) Nos. 1, 2, 3 and 4 are known to have occurred within a small fraction of a second of an intense lightning flash. According to a statement made by Mr. Cartwright to Professor Snoddy and communicated to the authors, there was a nearly simultaneous flash associated with No. 5. There is no definite information on this point with respect to Nos. 6 and 7.

(3) The paths of the strokes show somewhat varied character. Portions of strokes Nos. 1, 3, 4, 5 and 6 are long sections with slight curvature. All except No. 6 show sharp reversals, and por-

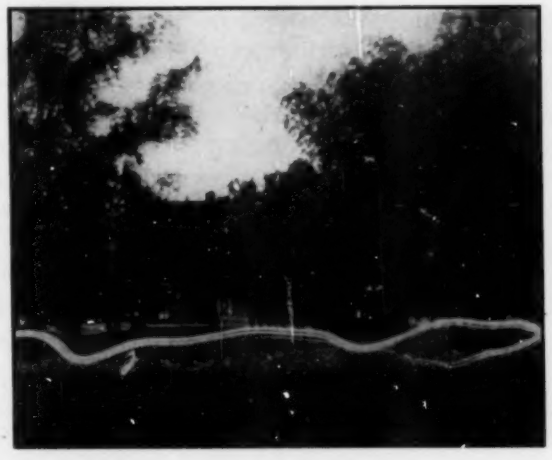

FIG. 5.

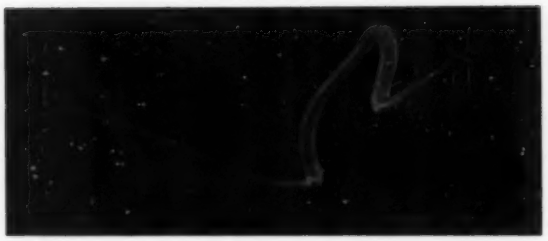

FIG. 6.

tions of Nos. 3, 4 and 7 are extremely irregular. Nos. 1 and 7 show variation of intensity along the path, or beading. Nos. 5 and 6 show a broad path of discharge.

(4) Whether or not thunder similar to that usually following intense lightning strokes is associated with these discharges is still uncertain. All observers report hearing thunder, but in the case of discharges 1 to 5 nearly simultaneous lightning strokes were observed. In the case of discharge 6, Larsen merely observed a bright illumination followed by thunder in less than a second.

CONCLUSIONS

Some suggestions as to the origin of these discharges are perhaps justified since several independent observations have been made. It is, of course, obvious that the present data do not permit of any certain conclusions, especially since no electrical data have yet been obtained. Since all of the discharges, with the possible exceptions of 6 and 7, were observed near ground objects during intense thunderstorms, it seems probable that there were large space charge concentrations in the vicinity of points on the ground objects. The sudden large variation in the magnitude and sign of the field due to a nearby stroke might serve as a trigger action for initiating these discharges. It is difficult, however, to suggest a process which would account for the observations on this assumption.

A somewhat more probable explanation might be found in the fact that a cloud ground lightning stroke produces a horizontally moving potential wave which may have transient horizontal gradients sufficiently great to initiate these discharges. This assumption is consistent with the observations that there is no evidence of direct hits to ground objects and that the strokes have large horizontal components of path. The rapid reversals in many parts of the photographs are certainly evidence of irregular fields and rapidly changing fields as might be expected on the basis of the above assumption.

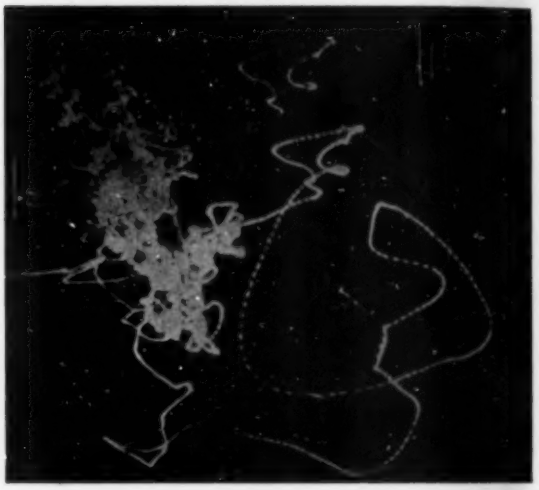

FIG. 7.

The discharges described here are probably not uncommon when the thunderstorm fields are very intense. Granting this, the question of their importance in producing damage arises. They could, of course, produce fires in inflammable matter. It is also possible that the existence of discharges of this kind might account for reports of bodily injury due to "lightning strokes" when the injury is slight.

We are indebted to Dr. C. G. Abbot of the Smithsonian Institution and to the editors of *Life* for permission to reproduce some of the photographs in this paper.

The photographs taken in New Mexico were obtained as a part of a research program supported by a grant from the Penrose Fund of the American Philosophical Society.

The Electrostatic Field Produced by a Point Charge in the Axis of a Cylinder

ERNST WEBER
Polytechnic Institute of Brooklyn, Brooklyn, New York
(Received March 22, 1939)

The general solution of the field distribution produced by a point charge at rest in the axis of a metallic cylinder is derived, and a simple approximation is given for the field strength on the surface of the cylinder.

SOLUTION OF THE POTENTIAL EQUATION

CHOOSING a cylindrical coordinate system as shown in Fig. 1, with the point charge of value Q located at the origin, it is obvious that close to the point charge the potential distribution must be given by

$$\phi' = k_e \frac{Q}{R} + \phi_0, \tag{1}$$

where

$$1/k_e = 4\pi\Delta_0\epsilon$$

$$R = (r^2+z^2)^{\frac{1}{2}}. \tag{2}$$

Δ_0 is the absolute dielectric constant of free space $((1/4\pi)\times(10^{-9}/9)$ farad/$m)$ and ϵ is the relative dielectric constant of the homogeneous medium within the cylinder (a numeric).

At any distance from the point charge the total potential will then be written

$$\phi = k_e Q\left[\frac{1}{R} + \varphi(r, z)\right] + \text{const.}, \tag{3}$$

where the function φ satisfies the Laplacean differential equation

$$\nabla^2\varphi(r, z) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right) + \frac{\partial^2\varphi}{\partial z^2} = 0. \tag{4}$$

Assuming φ as the product of two separable functions of only either r or z, and stipulating further symmetry in z with respect to the plane through the origin and normal to the axis, one can write the typical solution as

$$\bar{\varphi} = AJ_0(i\beta r)\cos\beta z = AI_0(\beta r)\cos\beta z, \tag{5}$$

where $J_0(i\beta r)$ is the Bessel function of the first kind and zeroth order, which customarily is denoted[1] by $I_0(\beta r)$. No other type of Bessel function could be used since the function φ must remain finite at the origin to preserve the point charge field there.

The parameter β is available for satisfying the boundary conditions. It is best to choose the general solution for φ in form of a Fourier integral with respect to β since obviously no periodicity could be expected. Thus the final form for the function φ will be

$$\varphi = \int_{-\infty}^{+\infty} A(\beta) I_0(\beta r)\cos\beta z\, d\beta \tag{6}$$

and the potential therefore is given by

$$\phi = k_e\frac{Q}{(r^2+z^2)^{\frac{1}{2}}} + k_e Q\int_{-\infty}^{+\infty} A(\beta) I_0(\beta r) \times\cos\beta z\cdot d\beta + \text{const.} \tag{7}$$

SATISFACTION OF BOUNDARY CONDITIONS

At the cylinder surface $r=a$ the potential must be given as a value ϕ_0, which might be ground

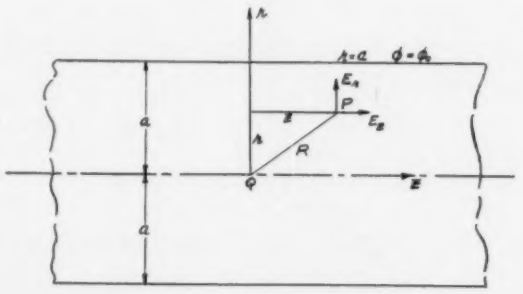

FIG. 1. The cylindrical coordinate system chosen: Q the point charge.

[1] See for example, N. W. McLachlan, *Bessel Functions for Engineers* (Oxford University Press, 1934). For most of the relations used see particularly the list of formulae pp. 160 to 164.

potential. Introducing $r=a$ and $\phi=\phi_0$ into Eq. (7) one has

$$\int_{-\infty}^{+\infty} A(\beta) I_0(\beta a) \cos \beta z d\beta = \frac{\phi_0 - \text{const.}}{k_e Q} - \frac{1}{(a^2+z^2)^{\frac{1}{2}}}. \quad (8)$$

The extremely valuable tables by Campbell-Foster[2] give as pair No. 918 the relation

$$\frac{1}{2(g^2+\sigma^2)^{\frac{1}{2}}} = \int_{-\infty}^{+\infty} K_0(\sigma|p|) \epsilon^{i2\pi f g} df, \quad (9)$$

where $|p| = |2\pi i f| = 2\pi|f|$, and where $K_0(\sigma|p|)$ denotes the modified Bessel function of the second kind and zeroth order. Now $K_0(\sigma|p|)$ is an even function on account of the absolute value of the argument, so that the exponential function in (9) can be replaced by the cos $(2\pi f g)$ since the sine-part vanishes on integration anyway. Replacing then g by z, $2\pi f$ by β, and σ by a, one has

$$\frac{1}{(z^2+a^2)^{\frac{1}{2}}} = \frac{1}{\pi} \int_{-\infty}^{+\infty} K_0(|\beta| a) \cos \beta z d\beta, \quad (10)$$

which can be used on the right-hand side of (8). Equating the constant terms gives

$$\text{const.} = \phi_0 \quad (11)$$

and equating the Fourier integral in (8) to the negative of (10) one has

$$A(\beta) = -\frac{1}{\pi} \frac{K_0(|\beta| a)}{I_0(\beta a)} \quad (12)$$

and the final form for the potential function becomes

$$\phi = \phi_0 + k_e Q \left[\frac{1}{(r^2+z^2)^{\frac{1}{2}}} - \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{K_0(|\beta| a)}{I_0(\beta a)} \cdot I_0(\beta r) \cos \beta z d\beta \right]. \quad (13)$$

Since $I_0(\beta a) > 1$, and $I_0(\beta r) \to 1$ as $r \to 0$, one can see with the aid of (10) that the Fourier integral will give a finite contribution close to the origin so that the character of the point charge field will be preserved there.

The Field Vector

Since

$$\frac{d}{dr} I_0(\beta r) = \beta \cdot I_1(\beta r),$$

one obtains for the field vector

$$E_r = -\frac{\partial \phi}{\partial r} = k_e Q \left[\frac{r}{(r^2+z^2)^{\frac{1}{2}}} + \frac{1}{\pi} \int_{-\infty}^{+\infty} \beta \cdot \frac{K_0(|\beta| a)}{I_0(\beta a)} I_1(\beta r) \cos \beta z d\beta \right], \quad (14)$$

$$E_z = -\frac{\partial \phi}{\partial z} = k_e Q \left[\frac{z}{(r^2+z^2)^{\frac{1}{2}}} - \frac{1}{\pi} \int_{-\infty}^{+\infty} \beta \frac{K_0(|\beta| a)}{I_0(\beta a)} I_0(\beta r) \sin \beta z d\beta \right]. \quad (15)$$

The actual evaluation of the field distribution is rather difficult on account of the Fourier integrals which necessitate a point for point numerical integration in infinite limits.

Introducing the notation

$$r/a = \rho, \quad z/a = \zeta, \quad -\beta a = \gamma, \quad (16)$$

one can write also

$$E_r = \frac{k_e Q}{a^2} \cdot \left\{ \frac{\rho}{(\rho^2+\zeta^2)^{\frac{1}{2}}} + \frac{2}{\pi} \int_0^{\infty} \gamma \frac{K_0(|\gamma|)}{I_0(\gamma)} \times I_1(\gamma\rho) \cos(\gamma\zeta) d\gamma \right\}, \quad (17)$$

$$E_z = \frac{k_e Q}{a^2} \cdot \left\{ \frac{\zeta}{(\rho^2+\zeta^2)^{\frac{1}{2}}} - \frac{2}{\pi} \int_0^{\infty} \gamma \frac{K_0(|\gamma|)}{I_0(\gamma)} \times I_0(\gamma\rho) \sin(\gamma\zeta) d\gamma \right\}, \quad (18)$$

where the first factor represents the field strength of the point charge on a sphere of radius a. Since the integrands in Eqs. (14) and (15) are even functions of the parameter β one can restrict integration to $\gamma > 0$ as done in Eqs. (17) and (18).

Along the plane of symmetry ($z=0$) as well as

[2] G. A. Campbell and R. M. Foster, *Fourier Integrals for Practical Applications* (Bell Telephone Monograph B-584, 1931).

on the surface of the cylinder, E_z vanishes and E_r takes on particularly simple forms, namely

$$E_{r/z=0}=\frac{k_e Q}{r^2}\left\{1+\frac{2}{\pi}\rho^2\int_0^\infty \gamma\frac{K_0(\gamma)}{I_0(\gamma)}I_1(\gamma\rho)d\gamma\right\}, \quad (17a)$$

$$E_{r/r=a}=\frac{k_e Q}{a^2}\left\{\frac{1}{(1+\zeta^2)^{\frac{1}{2}}}+\frac{2}{\pi}\int_0^\infty \gamma\frac{K_0(\gamma)}{I_0(\gamma)}I_1(\gamma)\cos(\gamma\zeta)d\gamma\right\}. \quad (18a)$$

Eq. (17a) shows that the field strength in the plane $z=0$ is at all points larger than the corresponding field strength of the point charge alone. From Eq. (18a) one can obtain the total charge induced on the cylinder. Since the surface charge density is given by

$$\eta=-\Delta_0\epsilon E_{r/r=a},$$

the total charge follows as

$$-2\pi a^2\Delta_0\epsilon\cdot 2\int_0^\infty E_{r/r=a}d\zeta. \quad (19)$$

Performing this integration on the first term in the brackets of (18a) one finds the value $(-Q)$ which is the negative equal of the point charge. The integration (19) performed on the second term in the brackets of (18a) must therefore give zero value, or also, the second term in (18a) represents the fictitious surface charge distribution, necessary to satisfy the condition of constant potential along the cylinder; this term must change sign.

Approximations for the Field Vector

The numerical evaluation of the integrals in (17a) and (18a) is very laborious. For values of the argument $\gamma>5$, however, the following approximations may be used[1]

$$I_0(\gamma)\cong I_1(\gamma)\cong\frac{\epsilon^\gamma}{(2\pi\gamma)^{\frac{1}{2}}}, \quad K_0(\gamma)\cong\left(\frac{\pi}{2\gamma}\right)^{\frac{1}{2}}\cdot\epsilon^{-\gamma} \quad (20)$$

and the integrations performed analytically.

A fair approximation for all values of $\gamma>0$ is found by direct plotting as[3]

$$\frac{K_0(\gamma)}{I_0(\gamma)}\cong(2\pi)^{\frac{1}{2}}\gamma\epsilon^{-2\gamma} \quad (21)$$

and using this in Eq. (17a), the integral can be solved[4]

$$\int_0^\infty \gamma\frac{K_0(\gamma)}{I_0(\gamma)}I_1(\gamma\rho)d\gamma=(2\pi)^{\frac{1}{2}}\int_0^\infty \gamma\epsilon^{-2\gamma}I_1(\gamma\rho)d\gamma=\frac{(2\pi)^{\frac{1}{2}}\rho}{(4-\rho^2)^{\frac{1}{2}}}, \quad (22)$$

leading to

$$E_{r/z=0}\cong\frac{k_e Q}{r^2}\left[1+\left(\frac{8}{\pi}\right)^{\frac{1}{2}}\left(\frac{\rho}{(4-\rho^2)^{\frac{1}{2}}}\right)^3\right]. \quad (23)$$

At the cylinder surface $\rho=1$ and the brackets take the value $[1+0.307]$ indicating an increase in the field strength by 30.7 percent on account of the presence of the cylinder. Fig. 2 shows the variation of the field strength with radius. Ob-

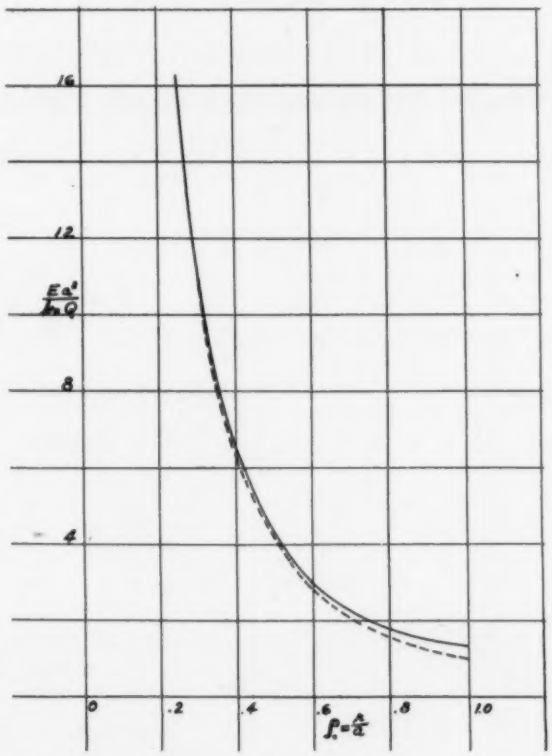

Fig. 2. Field strength E_r in plane of symmetry ($z=0$): sol'd line for point charge in cylinder, dash line for point charge alone.

[3] For the numerical computations the *Tables of Functions* by E. Jahnke and F. Emde (B. G. Teubner, Leipzig, 3rd edition, 1938), were used.

[4] Reference 1, p. 160, No. 45.

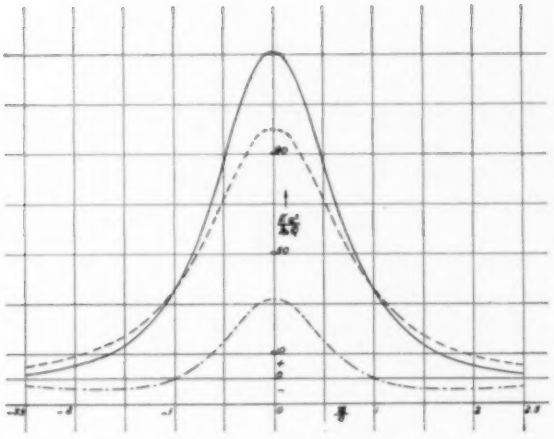

FIG. 3. Field strength E_r or charge density along the surface of the cylinder: solid line for point charge in cylinder, dash line for point charge alone, dash-dot line for compensating surface charge.

viously, the effect of the cylinder is not very marked in this case.

One can also approximate for all values of $\gamma>0$ again by direct plotting[3]

$$\gamma\frac{K_0(\gamma)}{I_0(\gamma)}I_1(\gamma)\leqq\frac{\gamma}{2}\epsilon^{-\gamma} \tag{24}$$

and write the integral in Eq. (18a) as[5]

$$\tfrac{1}{2}Re\int_0^\infty\gamma\epsilon^{-(1-i\zeta)\gamma}d\gamma=\tfrac{1}{2}Re\frac{1!}{(1-i\zeta)^2}=\frac{1-\zeta^2}{2(1+\zeta^2)^2}.$$

Thus the field strength becomes

$$E_{r/r=a}\leqq\frac{k_eQ}{a^2}\left[\frac{1}{(1+\zeta^2)^{\frac{1}{2}}}+\frac{1}{\pi}\frac{1-\zeta^2}{(1+\zeta^2)^2}\right]. \tag{25}$$

Using this expression in the integral (19) it is found to satisfy the physical conditions and moreover, for $\zeta=0$ the value of the brackets becomes $[1+0.318]$ which is in close agreement with the value from Eq. (23) for $\rho=1$. Fig. 3 then shows the distribution of field strength along the cylinder together with the component parts of the brackets.

[5] Reference 3, p. 20.

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Scientific Knowledge of the Pearl

In a recent research report by A. E. Alexander of Mellon Institute the attempts made by man to simulate the natural pearl are discussed. Despite human ingenuity and the wonders of science, no artificial or "cultured" pearl can be produced which can compare with that bit of loveliness from the Persian Gulf which is the handiwork of nature. And although cultured and imitation pearls are available, they bear a similar relationship to the natural pearl as gold-filled articles do to solid gold jewelry or silver plate to sterling.

The entirely natural formation of the genuine Oriental pearl occurs, for example, where by chance a tiny grain of sand or other foreign particle enters an oyster shell, or where some abnormal physiological condition results in the growth of a jewel. This tiny particle or disturbed area becomes the nucleus of the gem. Layer on layer of nacre is deposited upon this heart as the pearl grows. These films that form the pearl vary in thickness, being much thinner than a sheet of tissue paper. The most lustrous pearls are those in which the constituent layers are the thinnest, while those of less attractive appearance are made up of thicker and coarser layers of nacre.

It is generally believed that the pearl generally takes its color from the shell lining, and even from that part of the shell near which it is formed. A rose or cream colored pearl would not be expected, according to this explanation, in an oyster in which the shell lining is of any other color.

Chemically the pearl is composed almost entirely of calcium carbonate. This material, on examination, is found to be deposited around a tenuous network of organic matter (conchiolin) much like the enamel around the dentine of a tooth.

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Another ingenious method used to differentiate cultured pearls from the natural gems employs the "Endoscope," invented by Chilowsky and Perrin in 1926. By this apparatus, light is found to be totally reflected in the interior of a natural pearl, producing a characteristic flash, which does not occur when a cultured pearl is similarly tested by this method.

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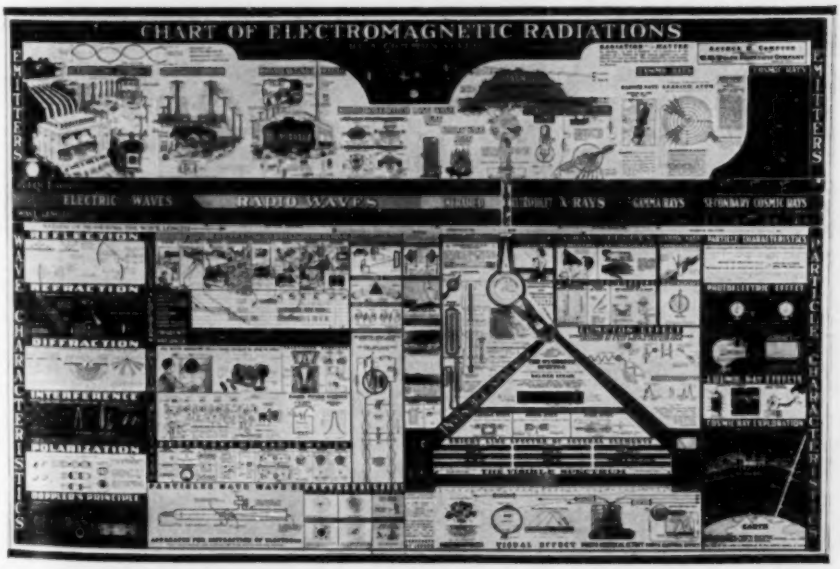

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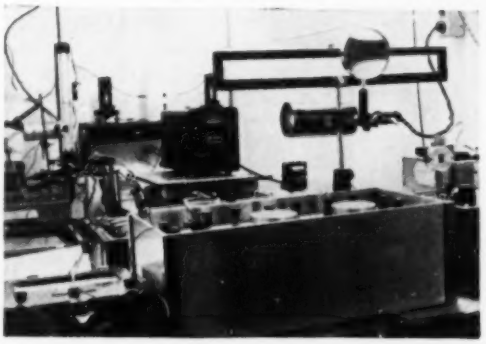

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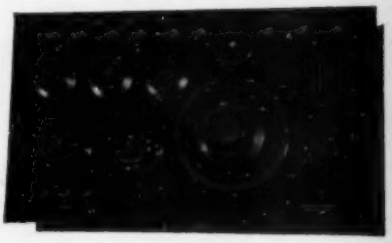

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